Analysis of $B^0 \rightarrow \rho^0 \rho^0$ Decays, CP Violation and Implications for the CKM Matrix

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- **For the BaBar Collaboration**

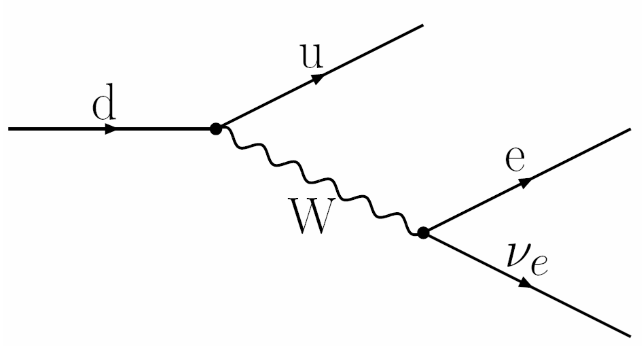
Outline

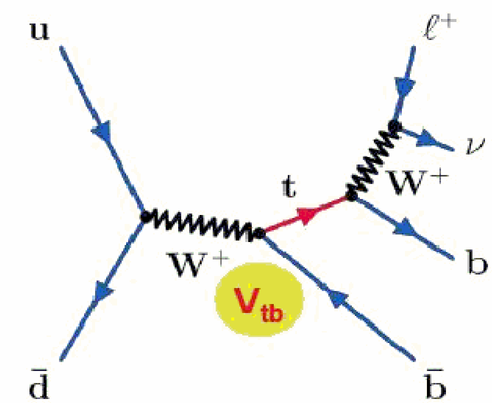
- Theory
  - EW Interactions → CKM Matrix → CP Violation → B mesons → ρρ system → $\rho^0\rho^0$
- The BaBar Experiment
  - Detector Components & Relevance
  - SVT Calibration
- Analysis
  - Event Selection & PDF construction.
  - Validation & Systematics.
  - Results & Implications for the CKM Matrix.

Setting The Context

Standard Model

- The Electro-Weak symmetry is broken via the Higgs mechanism.
- Quarks acquire masses and the generations (weakly) interact.
- Charged Current Interaction: $-\sqrt{\frac{1}{2}}g\overline{u_{Li}}\gamma^{\mu}\overline{V}_{ij}d_{Lj}W_{\mu}^{+} + \text{h.c.}$





- V (i,j=1,2,3) is the Cabibbo-Kobayashi-Maskawa (CKM) matrix.

CKM Matrix

❖ Describes the mixing between three generations of quarks.

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \quad : \quad |V_{CKM}| \simeq \begin{pmatrix} 0.975 & 0.221 & 0.003 \\ -0.221 & 0.975 & 0.040 \\ 0.009 & 0.039 & 0.999 \end{pmatrix}$$

❖ Parameterized by 3 mixing angles and a phase.

Wolfenstein parameterization

$$\begin{pmatrix} \mathbf{1-\lambda^2} & \boldsymbol{\lambda} & \mathbf{A\,\lambda^3(\rho-i\eta)} \\ \mathbf{-\lambda} & \mathbf{1-\lambda^2/2} & \mathbf{A\,\lambda^2} \\ \mathbf{A\lambda^3(1-\rho-i\eta)} & \mathbf{-A\,\lambda^2} & \mathbf{1} \end{pmatrix}$$

❖ CP Symmetry is violated for a nonzero phase ($\eta/\rho \approx 2.5$).

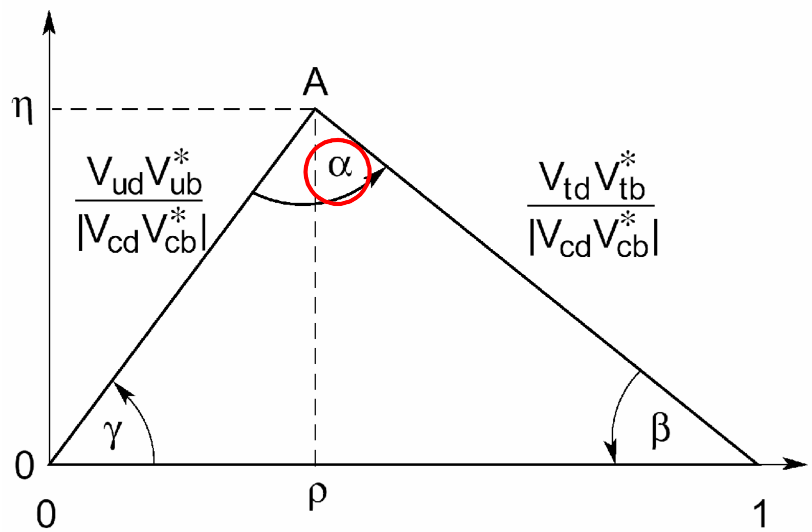
CP Violation

- Unitarity of CKM matrix implies:

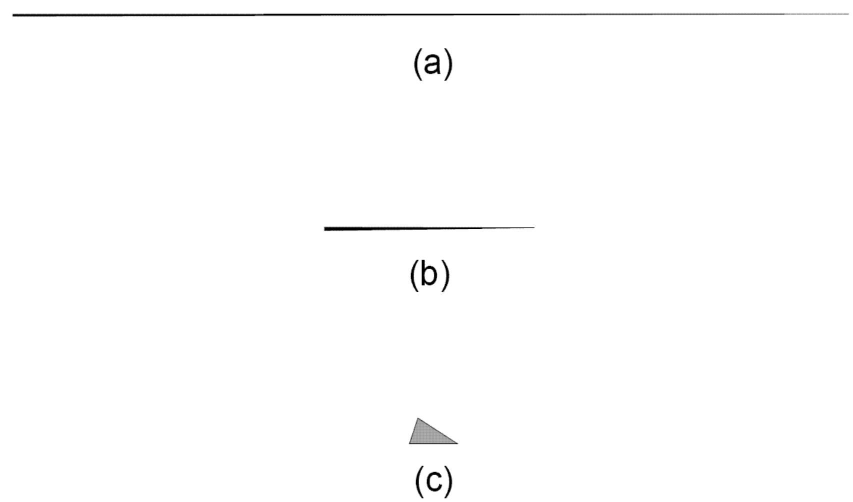
$$a)\ K:\ V_{id}V_{is}^* = V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0$$

$$b)\ B_s:\ V_{is}V_{ib}^* = V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

$$c)\ B_d:\ V_{id}V_{ib}^* = V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



- $\alpha = -arg[V_{td}V^*_{tb}/V_{ud}V^*_{ub}]$

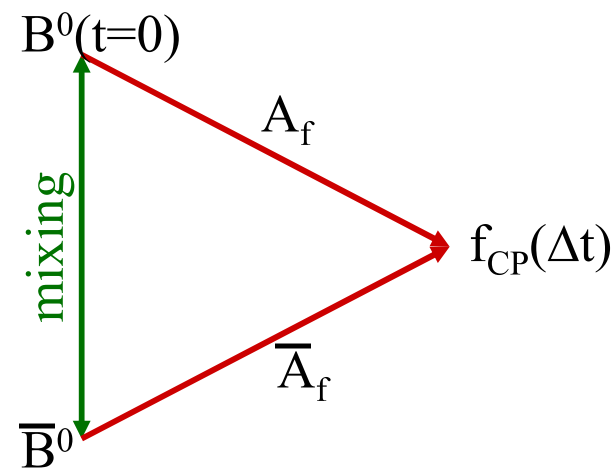


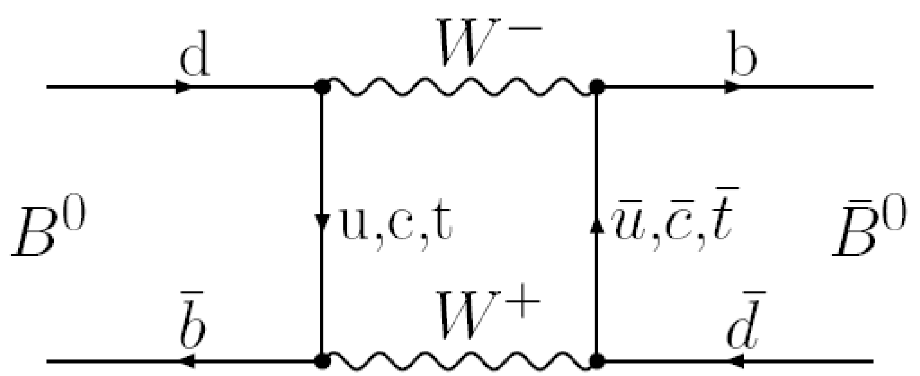
- Triangle Area Corresponds to the amount of CP violation (same for K, B_s, B_d).
- 'Openness' of (c) points to the presence of large CP asymmetries.

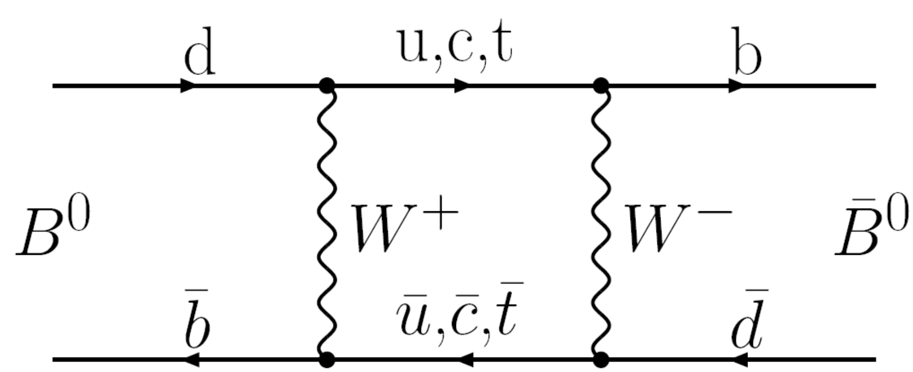
B Meson Decays

❖ Provide information about the angles and sides of the unitarity triangle.

❖ We study the B^0 - $\overline{B}^0$ oscillations:







❖ The interference between a direct decay and such oscillation enables us to measure the size of the CP violation.

Mass Mixing & Time Dependence

- The mass-eigenstates are:

$$|B_L>= p|B^0> +q|\overline{B}^0>,\ |B_H>= p|B^0> -q|\overline{B}^0>$$

- |p|~|q|

- The rate for producing the CP final state is:

direct decay *mixing*

$$R(\Delta t) \propto e^{-\Gamma(\Delta t)}\{1 \pm C_{CP}\cos[\Delta m_B \Delta t)] \mp S_{CP}\sin[\Delta m_B \Delta t)]\}$$

where $\Delta m_B = m_H - m_L$, S_{CP} & C_{CP} are functions of $A_f \equiv< f|H|B^0>$, $\bar{A}_f \equiv< f|H|\overline{B}^0>$

❖ ρρ Case:

- Vector-vector state, which can decay via S, P or D waves.
- Our final state (f) is the $\rho^0\rho^0$ *Longitudinal* state.
- S_{CP}, C_{CP} are determined via the TD analysis.

Physics of CP Coefficients

❖ We measure the asymmetry

$$a_{f_{CP}}(t) \equiv \frac{\Gamma(B^0(t) \to f_{CP}) - \Gamma(\overline{B}^0(t) \to f_{CP})}{\Gamma(B^0(t) \to f_{CP}) + \Gamma(\overline{B}^0(t) \to f_{CP})} = C_{CP}\cos(\Delta m_B t) - S_{CP}\sin(\Delta m_B t)$$

$$S_{CP} = \frac{2Im(\lambda_{f_{CP}})}{1+|\lambda_{f_{CP}}|^2} \qquad \lambda_{f_{CP}} \equiv \frac{q\bar{A}_{f_{CP}}}{pA_{f_{CP}}} = \eta_{f_{CP}}\frac{q\bar{A}_{\bar{f}_{CP}}}{pA_{f_{CP}}}$$

- S_{CP} corresponds to CP violation due to mixing.
- $S_{CP}=\sin(2\alpha)$ when Penguin Loop corrections are neglected.

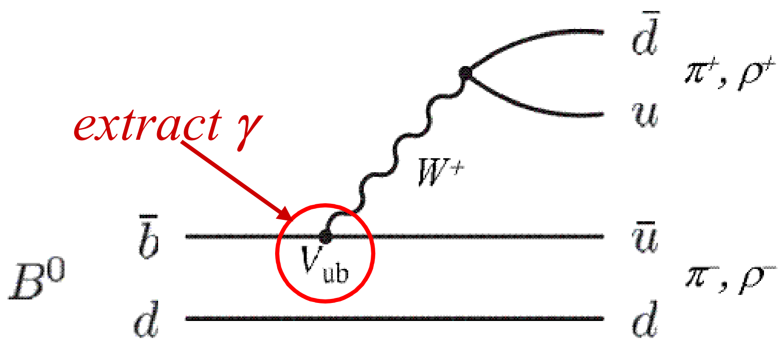
$$C_{CP} = \frac{1-|\lambda_{f_{CP}}|^2}{1+|\lambda_{f_{CP}}|^2}$$

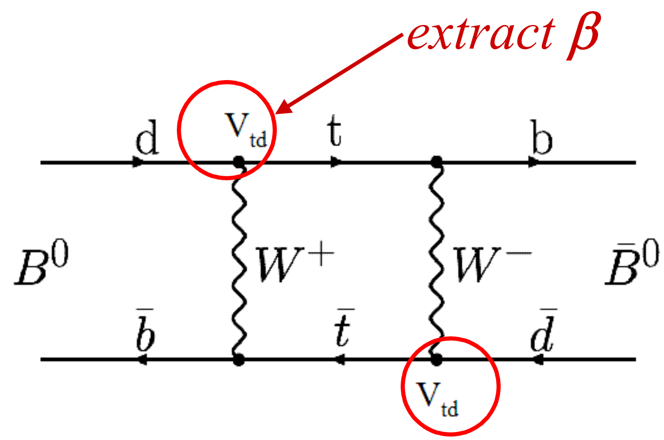
- C_{CP} corresponds to direct CP violation (with final states having different phases).
- $C_{CP}= 0$ at tree level.

❖ Non Standard Model physics can affect either type of CP violation

Measuring α

❖ **Several possible processes.**





❖ **Measure $\alpha=180^o-\beta-\gamma$ via weak phases.**

➢ Original attempt: measure S_{CP} in $B\rightarrow\pi^+\pi^-$.

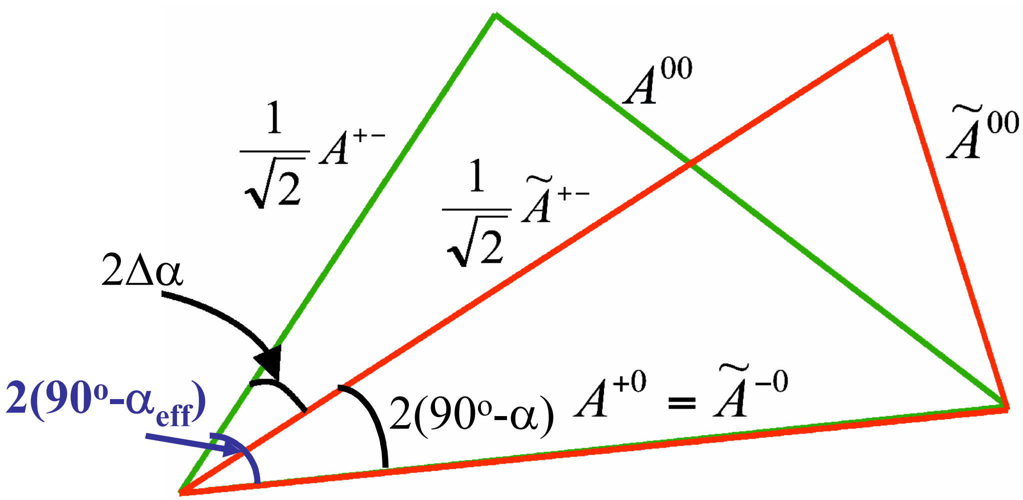
➢ Large loop corrections require knowledge of CP parameters in $B\rightarrow\pi^+\pi^0$, $B\rightarrow\pi^0\pi^0$ as well.

➢ Not possible to obtain time (vertex) information for $B\rightarrow\pi^0\pi^0$.

❖ **$B\rightarrow\rho\rho$ we can perform the full Isospin Analysis.**

ρρ System & Isospin

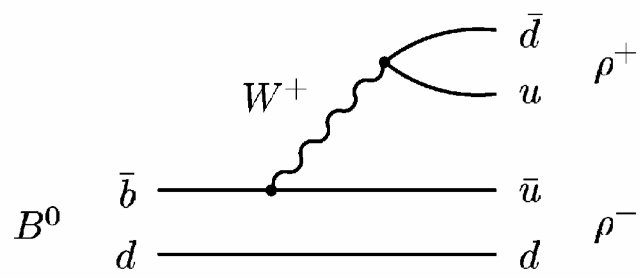
- The three decays $B\to\rho^0\rho^0$, $B\to\rho^+\rho^0$, $B\to\rho^+\rho^-$ only have two (longitudinal) final states (I=0,2).
- The (strong & weak) phases can be related to each other & Unitarity Angles.
- We represent relations between the amplitudes as triangles in the Complex Plane.



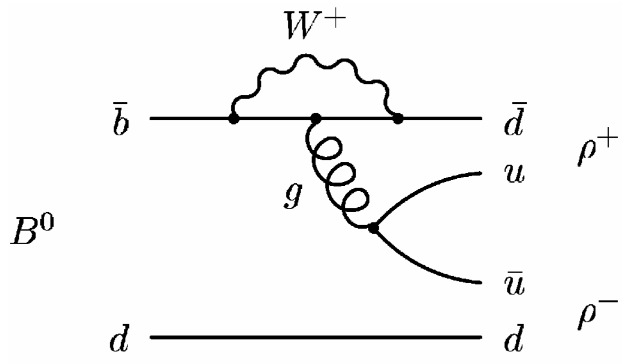
$$
\begin{aligned}
A^{+-} &= A(B^0 \to \rho^+\rho^-)\\
\tilde{A}^{+-} &= A(\overline{B}^0 \to \rho^+\rho^-)\\
A^{00} &= A(B^0 \to \rho^0\rho^0)\\
\tilde{A}^{00} &= A(\overline{B}^0 \to \rho^0\rho^0)\\
A^{+0} &= A(B^+ \to \rho^+\rho^0)\\
\tilde{A}^{-0} &= A(B^- \to \rho^-\rho^0)
\end{aligned}
$$

- We retain the four-fold ambiguity with respect to orientation of the triangles.

$\rho^+\rho^-$



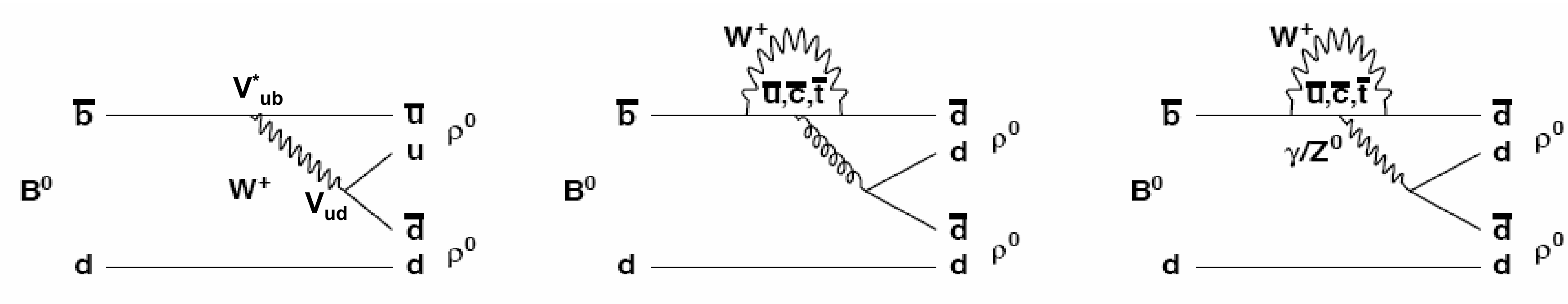
Tree Level



Leading Penguin

- The Tree Diagram ***is not*** color suppressed ($BR=23.5\times10^{-6}$) .
- The Leading Penguin is suppressed.
- The process can be used to evaluate α_{eff} .
- $S_{CP}=(\sqrt{1-C_{CP}^2})\sin(2\alpha-2\Delta\alpha)$ or $S_{CP} \equiv(\sqrt{1-C_{CP}^2})\sin(2\alpha_{eff})$.

$\rho^0\rho^0$



Tree Level *Strong Penguin* *Electro-Weak Penguin*

❖ **Unlike $\pi^0\pi^0$ we can fully reconstruct the decay vertices.**

➢ The Tree Diagram ***is*** color suppressed.

➢ The Penguin Loop corrections make a significant contribution (~20%).

➢ The Electro-Weak Penguins generate final states with different hadronic and CKM phases.

➢ We place limits on Penguin Contributions $\Delta\alpha$.

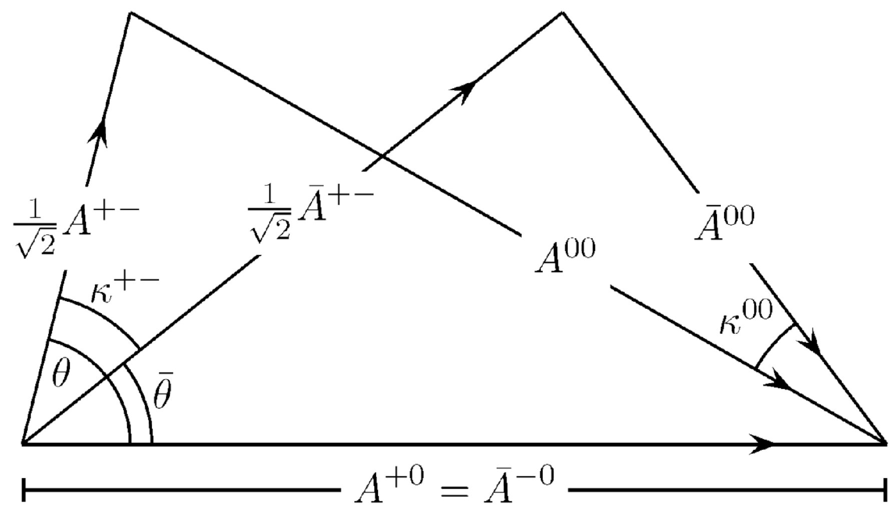
Determining α

❖ **Construct a $\chi^2(\alpha)$.**

$$\chi^2 = \chi^2(\alpha, S^{+-}, S^{00}, C^{+-}, C^{00}, B^{+-}_{Tot}, B^{+0}_{Tot}, B^{00}_{Tot}, f_L^{+-}, f_L^{+0}, f_L^{00}, \tilde{S}^{+-}, \sigma^2(\tilde{S}^{+-}), \tilde{S}^{00}, \sigma^2(\tilde{S}^{00}), \ldots)$$
$$= \chi^2(\alpha, A_0, A_2, \bar{A}_0, \bar{A}_2, \tilde{S}^{+-}, \sigma^2(\tilde{S}^{+-}), \tilde{S}^{00}, \sigma^2(\tilde{S}^{00}), \ldots)$$

- The measured quantities are denoted by ~ .

- All 10 parameters are expressed in terms of the four amplitudes $(A_0, A_2, \bar{A}_0, \bar{A}_2)$.



❖ **We minimize $\chi^2(\alpha)$, while scanning over α.**

Objectives

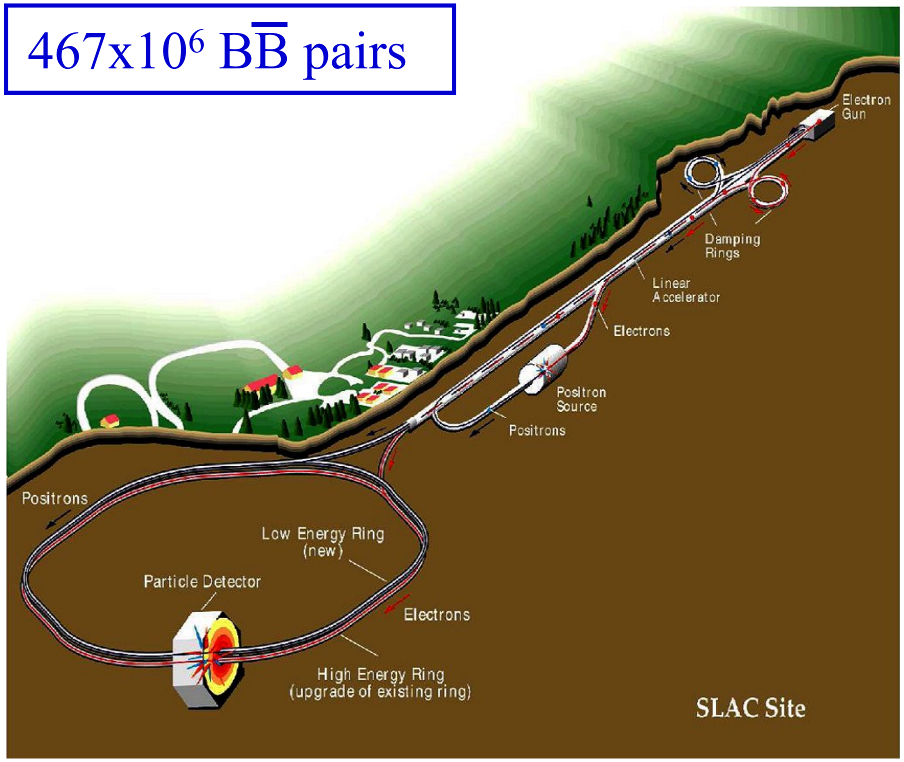
- ❖ Examine The Electro-Weak interactions in the Standard Model, specifically focusing on CP properties of B decays.
- ❖ Measure the BR and CP coefficients in $B \rightarrow \rho^0 \rho^0$ decays.
- ❖ Use the above to place a limit on $\Delta\alpha$.

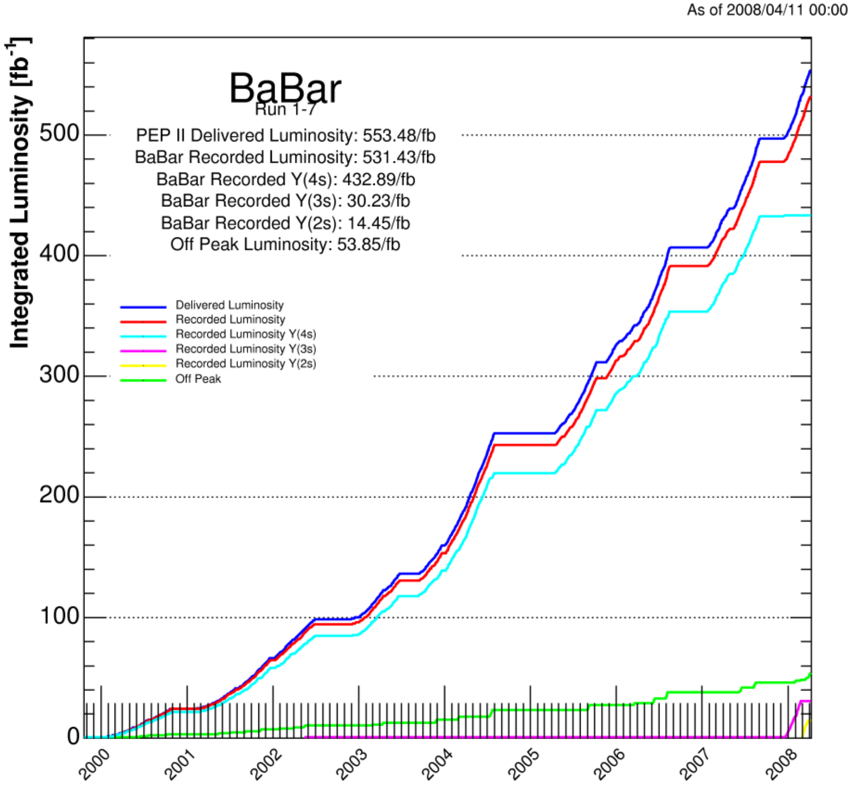
BaBar Experiment

PEP-II & BaBar

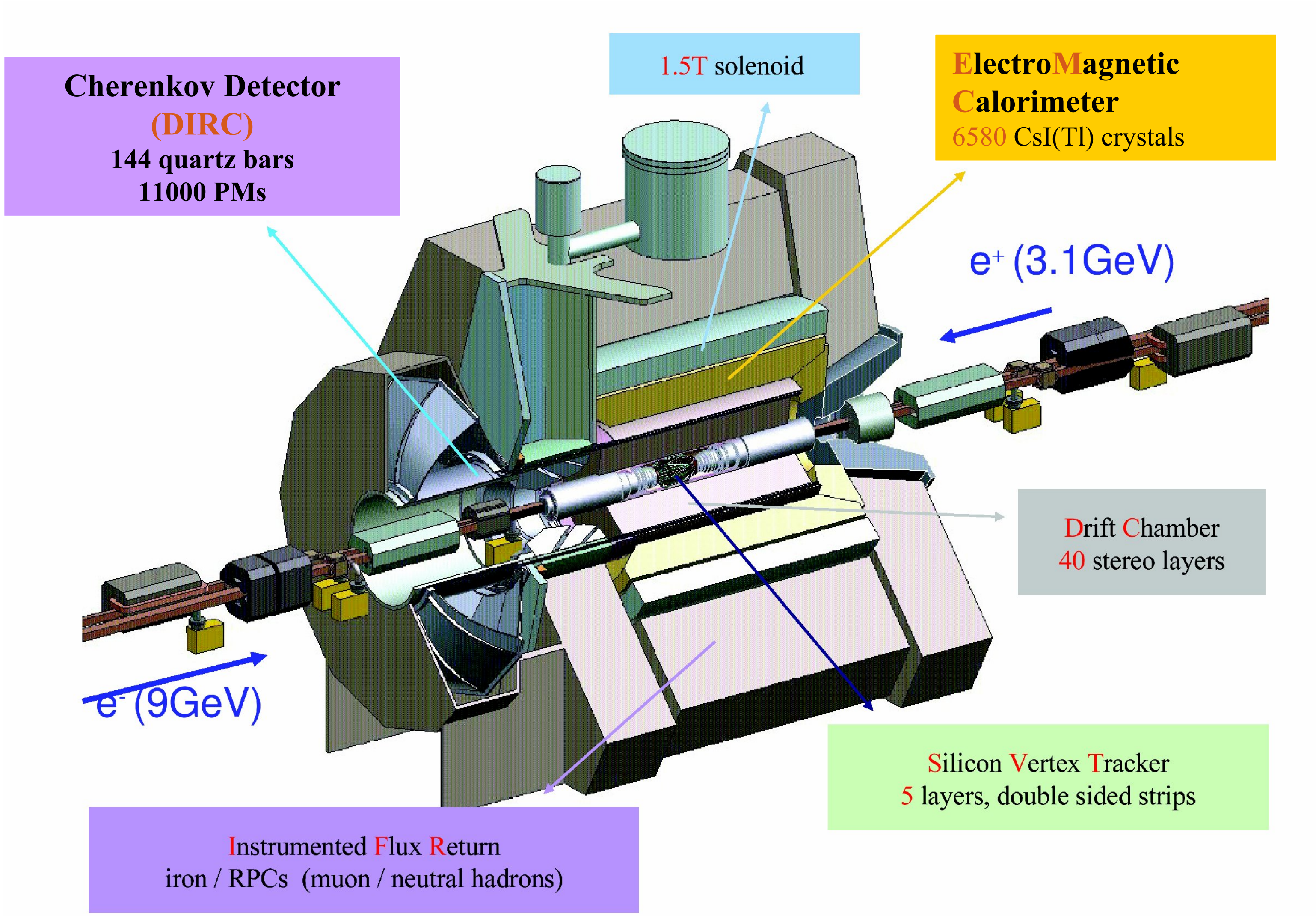
❖ PEP-II is an asymmetric B-factory
❖ $e^-(9GeV)e^+(3.1GeV) \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$

467×10^6 $B\bar{B}$ pairs



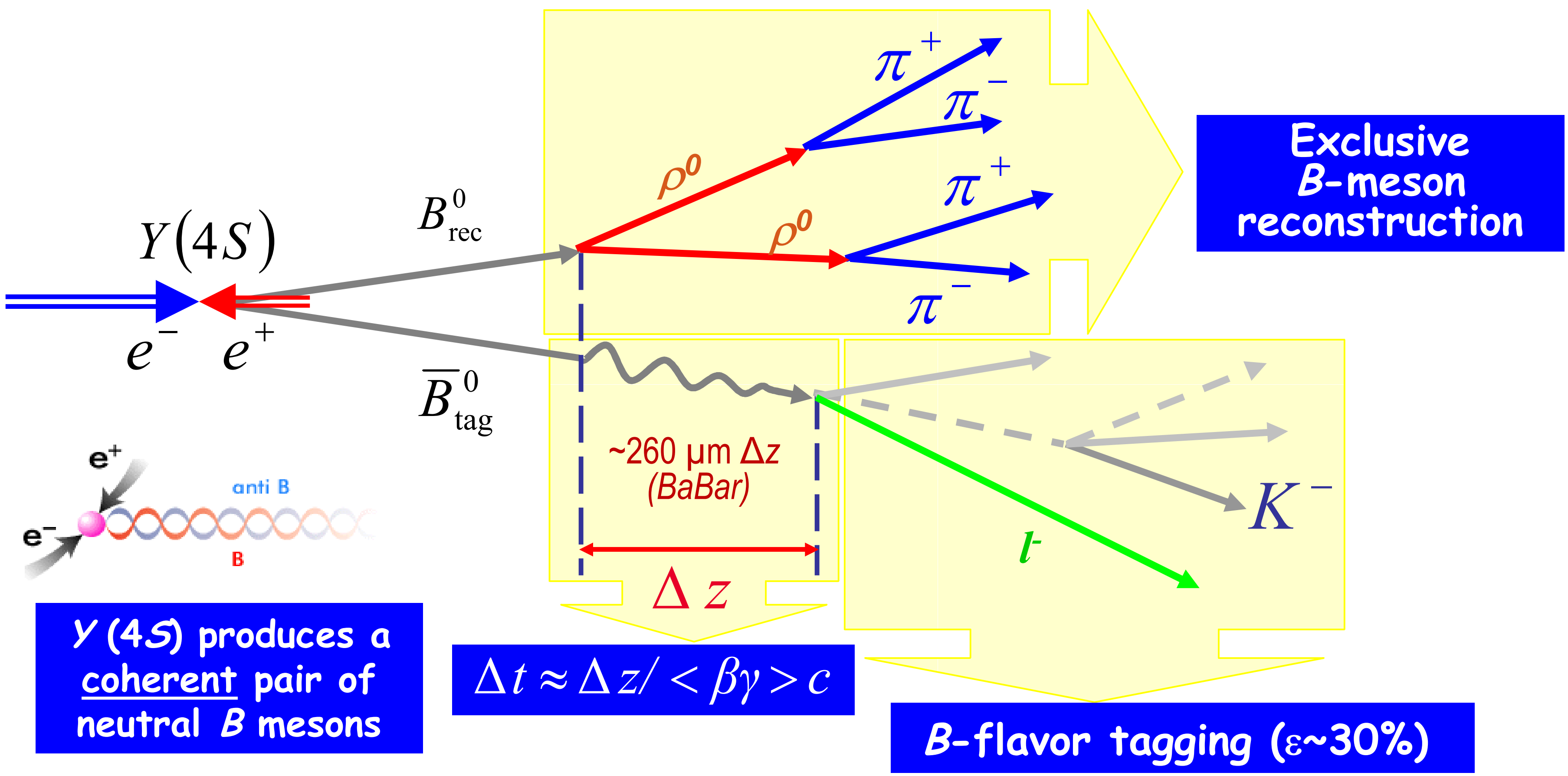


The Detector



The Decay

- $B^0 \to \rho^0\rho^0 \to \pi^+\pi^-\pi^+\pi^-$ (~100 evts.).



Subsystems

- **Reconstruct the decay vertices.**
- **Reconstruct the exclusive final state.**
- **Determine the flavor of the conjugate B^0.**

❖ Silicon Vertex Tracker (SVT)

- Energy loss on the silicon strips, enabling precise vertex reconstruction & charged Particle ID (PID).

❖ The Drift Chamber (DCH)

- Ionization of the helium based gas allowing for precise momentum measurements & PID.

❖ Detector of Internally Reflected Cherenkov Radiation (DIRC)

- Track velocity based on the Cherenkov Angle, primarily distinguishing Pions & Kaons.

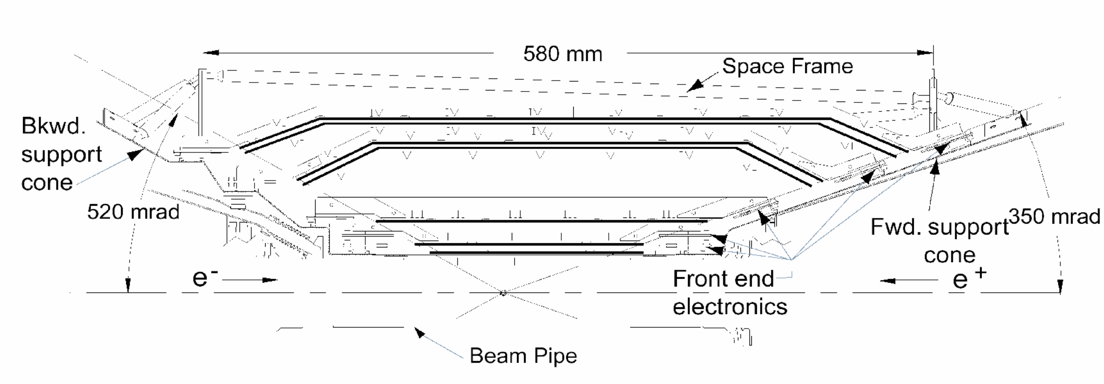
❖ Electromagnetic Calorimeter (EMC)

- Energy & position of e^-, γ, π^0 by absorbing their energy.

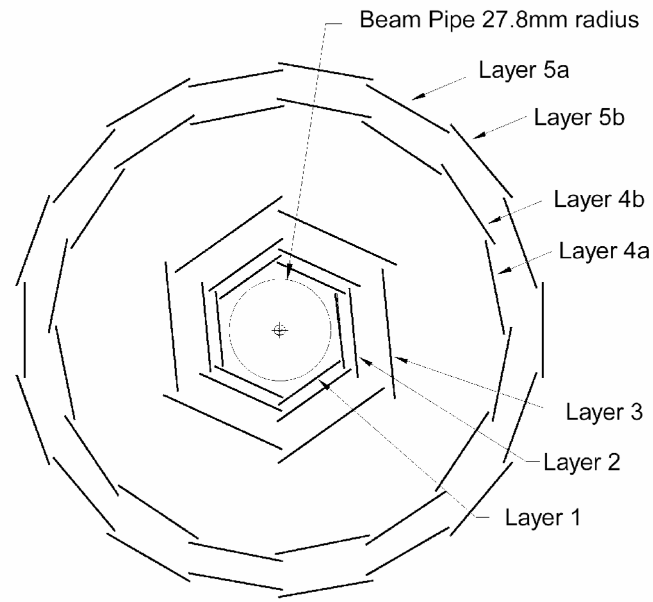
❖ Instrumented Flux Return (IFR)

- Presence of muons and neutral hadrons, which were able to penetrate other subdetectors.

SVT

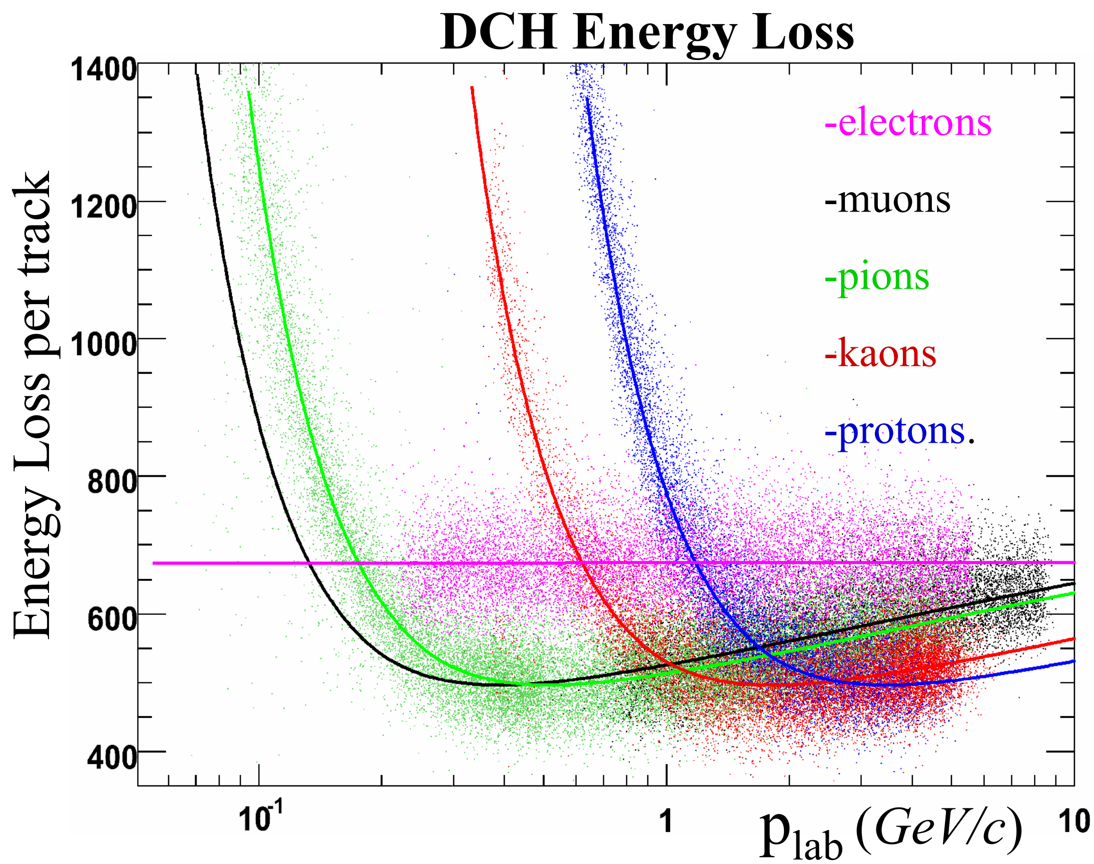


- Five concentric cylindrical layers of double-sided silicon detectors.
- Reconstructs the decay vertices of the two B^0-mesons (essential for measurement of CP asymmetries).
- Measures Specific Ionization per hit.
- Momentum information (by inverting the Bethe-Bloch curve).



Energy Loss

➢ **For the moderately relativistic (charged) particles most of the energy loss occurs via ionization and atomic excitation.**



❖ **Described by the Bethe-Bloch equation: $-dE/dx \sim (C * Ln(\beta\gamma) - \beta^2 - \delta)/\beta^2$**

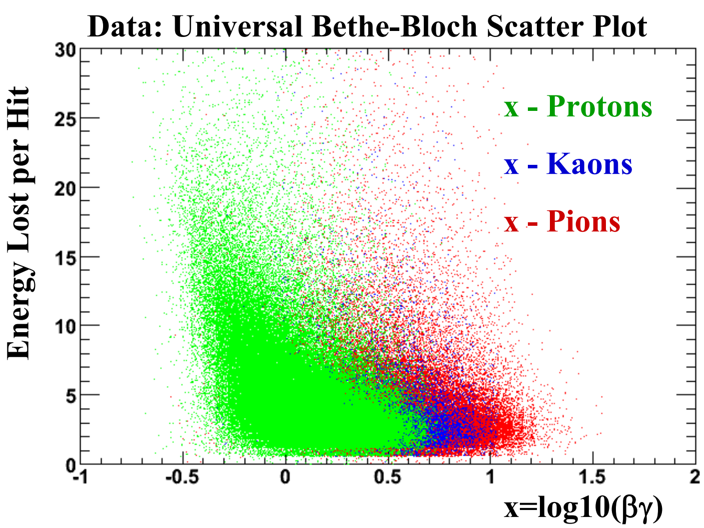
SVT Calibration & Tracking

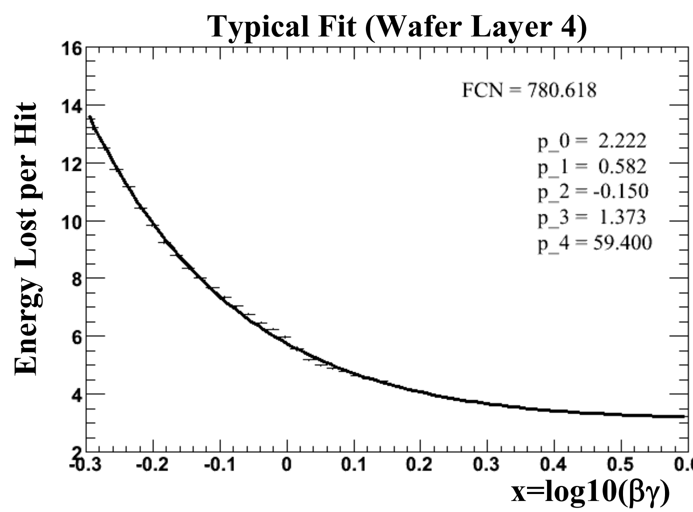
- **The actual energy loss is dependent upon *time*, θ, ϕ and the particle momentum.**
- **$dE/dx=dE/dx[\mathit{log}(\beta\gamma), C(\theta,\phi, \mathit{log}(\beta\gamma)), C_0(\theta), C_1(\theta), C_2(\theta), C_3(\theta), C_4(\theta)]$**
  the calibration constants $C, C_0, C_1, \ldots$ were determined by A. Telnov.
- **The (approximate) inverse can be used to provide momentum information.**
- **I have integrated these into the BaBar software.**
- **In the low momentum region particles lose a significant portion of their momentum with each interaction.**
- **Thus energy loss significantly varies between hits, making the (track based) truncated mean approach insufficient.**

Hit By Hit Model

❖ **Work in progress with the ultimate goal of improving track reconstruction, resolution and efficiency (particularly for low energy π's).**

✓ Examining the individual energy loss (both Φ & Z views) and accounting for dominant geometric effects.
✓ Producing sufficiently pure particle samples and using them to analyze energy loss within particular momentum ranges.
➢ Modeling the dependence of energy loss for each relevant variable (θ, ϕ , layer, *etc.*).
➢ Combining the measurements to produce a hit dependent equivalent to the Bethe-Bloch.





Analysis

Analysis Outline

- Controlling Backgrounds I: Parameters & Cuts
- Controlling Backgrounds II: PDF Fits
- Time Dependence
- Fit Yields & Validations
- Systematics
- Results & Implications

Parameters

❖ **Goal: Optimize the signal, while minimizing the backgrounds.**

➢ **Select the desired ranges for:**

➢ B^0 mass, reconstructed from beam energy ($5.245 < m_{ES} < 5.29$ GeV/c^2).

➢ The Difference between reconstructed B-energy and beam value ($|\Delta E| < 0.085$ GeV).

➢ Reconstructed masses of the ρ^0 mesons ($0.55 < m_1 m_2 < 1.05$ GeV/c^2).

➢ Helicities (*aka* decay angles) of the ρ^0 mesons ($|\cos\theta_1|, |\cos\theta_2| < 0.98$).

➢ Time between the decay of the two B's ($|\Delta t| < 15$ps) and its error ($0.1 < \Delta t_{Error} < 2.5$).

➢ Tagging Categories for the other B (six possibilities).

➢ Discriminant constructed to distinguish signal from continuum background (|*E-shape*|<2 or |L-shape|<5).

Discriminants I

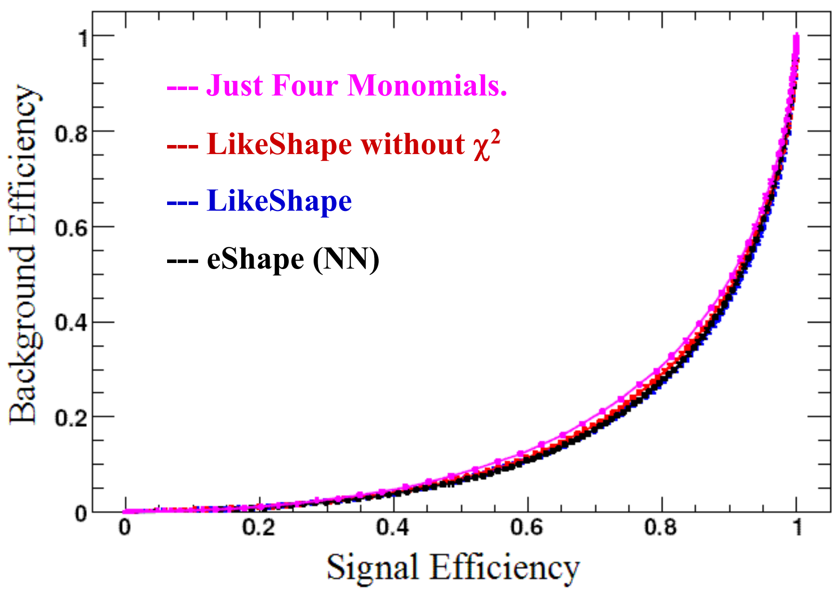
❖ **Distinguish 'jetty' background events from the 'symmetric' $B\bar{B}$ events.**

❖ **Neural Net Multivariate (eShape) *vs.* Likelihood Based (LikeShape).**

❖ Variables:

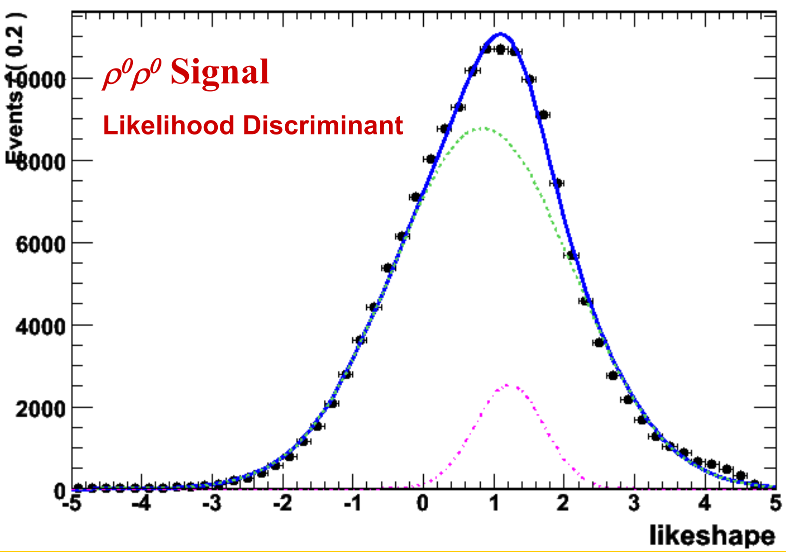
- Monomials $L_0^{charged}$, $L_0^{neutral}$, $L_2^{charged}$, $L_2^{neutral}$.
- vertex χ^2 probability.
- $\cos\theta_{BT}$ (angle between B thrust and ROE thrust).
- $\cos\theta_{ThBa}$ (polar angle of B thrust in CMS).
- $\cos\theta_B$ (polar angle of B momentum in CMS)

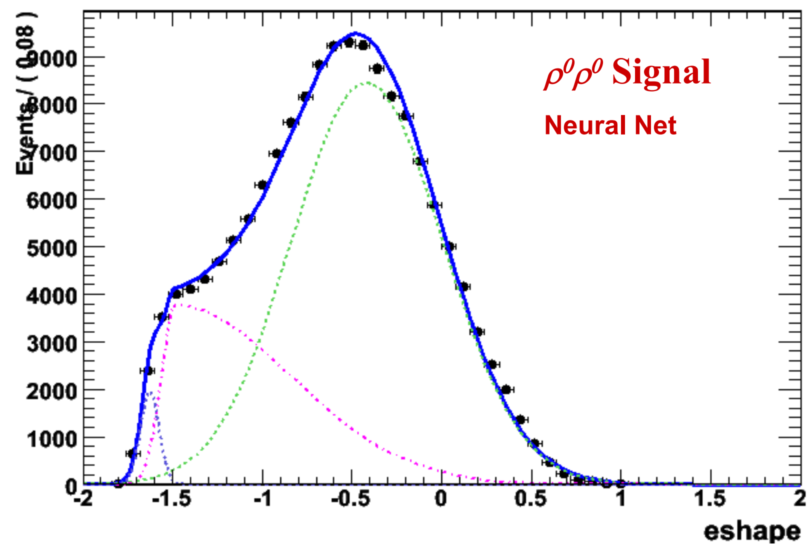
Discriminant Comparison



Discriminants II

- ❖ **Neural Net Multivariate Discriminant.**
  - ➢ Used in the Standard Fitter.
  - ➢ Gives the greatest possible discriminating ability.
- ❖ **Alternative: Likelihood Based Discriminant.**
  - ➢ One of the first analyses in BaBar to use the technique.
  - ➢ Not a ‘black box’.
  - ➢ Simpler PDF parameterizations for most modes.





Discriminants III

❖ **Perform Each Fit & Compare the Errors.**

LikeShape

Quantity	Mean Stat Error	Systematic Error	Total Error
nFullSig	**25.71** +/- 0.18	**0.688**	25.72
S	1.04 +/- 0.03	0.006	1.04
C	0.82 +/- 0.03	0.044	0.82

eShape

Quantity	Mean Stat Error	Systematic Error	Total Error
nFullSig	**25.81** +/- 0.19	**3.266**	26.02
S	1.01 +/- 0.03	0.022	1.01
C	0.83 +/- 0.03	0.047	0.83

- LikeShape reduces the Systematic Error by 4.7-times or 2.6 evts.
- Statistical Error Dominates & the collaboration chose to keep eShape as the default.

D-Veto

❖ **Goal: remove the D backgrounds, which have a signal-like peak.**

➢ Vetoed by placing restrictions on reconstructed D-masses.

$$|m_{K\pi\pi} - m_{D+}| > 13.6\ MeV$$

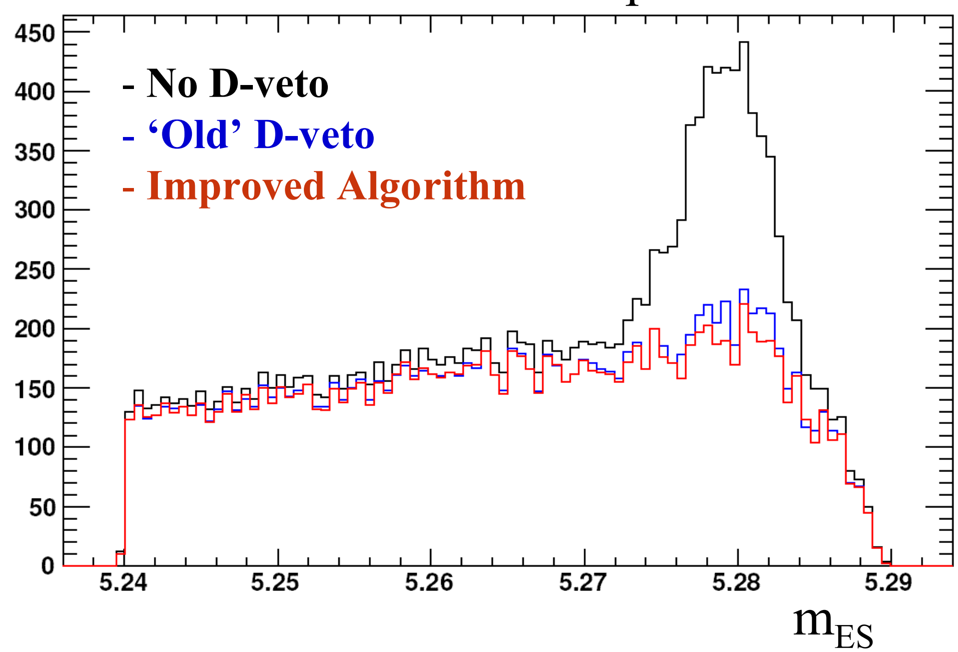
or

$$|m_{K\pi\pi} - m_{D+}| > 40.0\ MeV$$

and

$$|m_{\pi\pi\pi} - m_{D+}| > 13.6\ MeV$$

D-Veto Impact

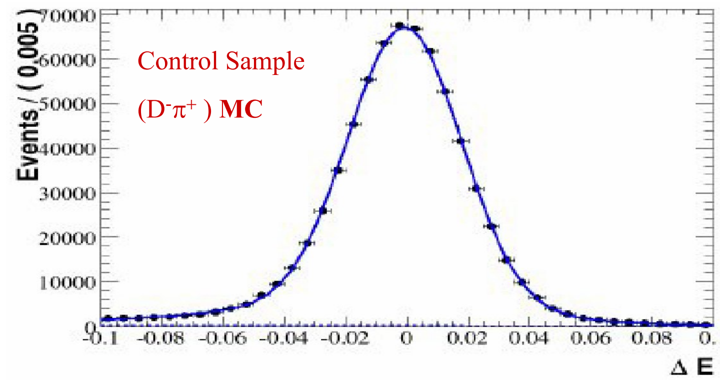


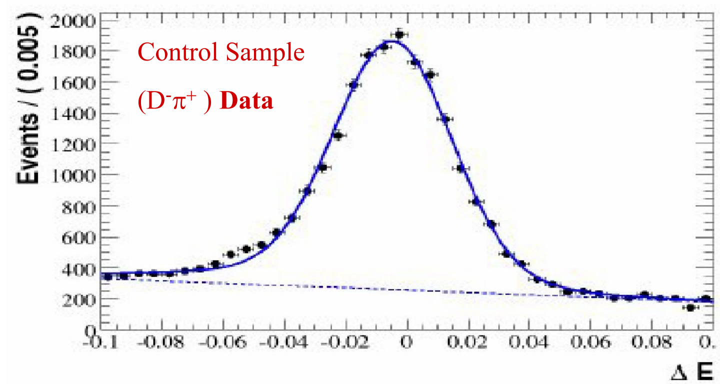
❖ Implemented an improved algorithm for selecting the 'fast' π.

Control Sample Studies

❖ **Goal: Account for discrepancies between Data & MC**

- Use $B^0 \rightarrow D^-\pi^+ \rightarrow (K^+\pi^-\pi^-)\pi^+$ control sample to calibrate ΔE, m_{ES} and eShape parameters.
- Make the necessary modifications to the parameters.
- Obtain the errors to be used in Error Analysis of the PDF shape uncertainty.





Candidate Selection

❖ We have multiple candidates for the same event (~5%).

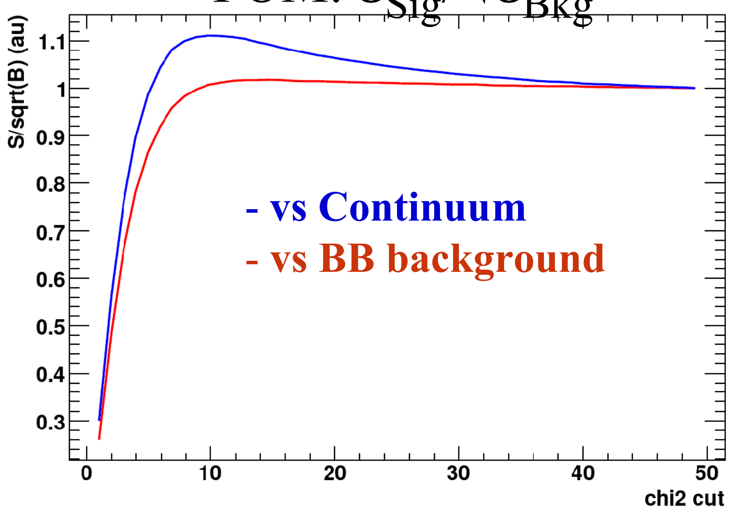
❖ Goal: Determine which approach yields the smallest combination of statistical and systematic error.

(1) Random: Signal Efficiency ε_{Sig}=0.87.

(2) Based on best χ^2 vertex: ε_{Sig}=0.92.

(3) Based on best χ^2 ΔE, m_1, m_2 (with or without vertex info): ε_{Sig}=0.97

FOM: $\varepsilon_{Sig}/\sqrt{\varepsilon_{Bkg}}$

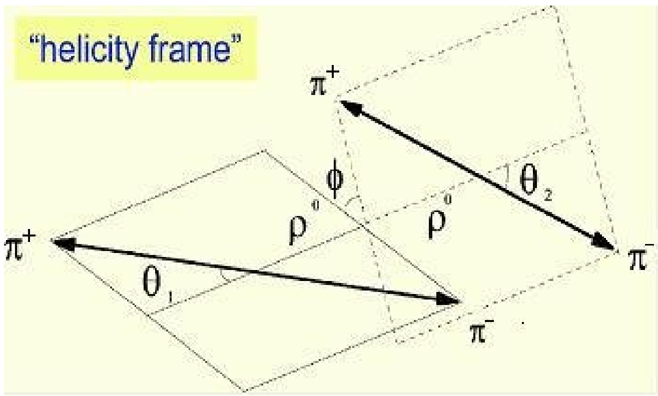


☞ **Use (2) since (3) introduces large correlations between the signal & backgrounds.**

Component PDFs

❖ **In addition to $B^0 \rightarrow \rho^0\rho^0$ (~100evts.) there are a number of problematic backgrounds in the signal region.**

➢ Fit in m_{ES}, ΔE, eShape, $m(\pi\pi)_{1,2}$, $\cos\theta_{1,2}$, tagging category, Δt.



➢ Combine & Construct a ML Fit.

$$L = \exp\Big(\underbrace{-\sum_i n_i}_{\text{yield term}}\Big)\prod_{j=1}^{N}\Big(\underbrace{\sum_i n_i f_i(\vec{x}_j;\vec{\theta})}_{\text{PDF term}}\Big) \rightarrow \max$$

n_i : yield of each event type (fixed or free
f_i : PDF for each event type
x_j : variables for each event
θ : PDF parameters (fixed or free)

➢ **A major portion of the analysis is to Isolate, Fit & Examine these PDFs.**

Backgrounds I

❖ **PDFs resemble the signal**

More Signal-Like

- ❖ Non Resonant Modes: $B^0 \to \rho^0 \pi^+ \pi^-$, $B^0 \to \pi^+ \pi^- \pi^+ \pi^-$. (~0 evts.).
  - ➢ Particularly problematic to extract.
- ❖ Secondary Signal Modes: $B^0 \to \rho^0 f_0(980)$ and $B^0 \to f_0 f_0$ (~10evts.).
- ❖ $B^0 \to a_1^+ \pi^- \to \pi^+ \pi^- \pi^+ \pi^-$ (~250 evts.).
  - ➢ Signal-like in m_{ES} and ΔE.
  - ➢ Interferes with the signal modes & is the main source of systematic error.
- ❖ Signal-Like Charmless Modes: $B^0 \to \rho^0 K^{*0}$, $B^0 \to f_0 K^{*0}$ (~100 evts.).
  - ➢ Fit PDFs Individually.
  - ➢ Control Overall Yields.

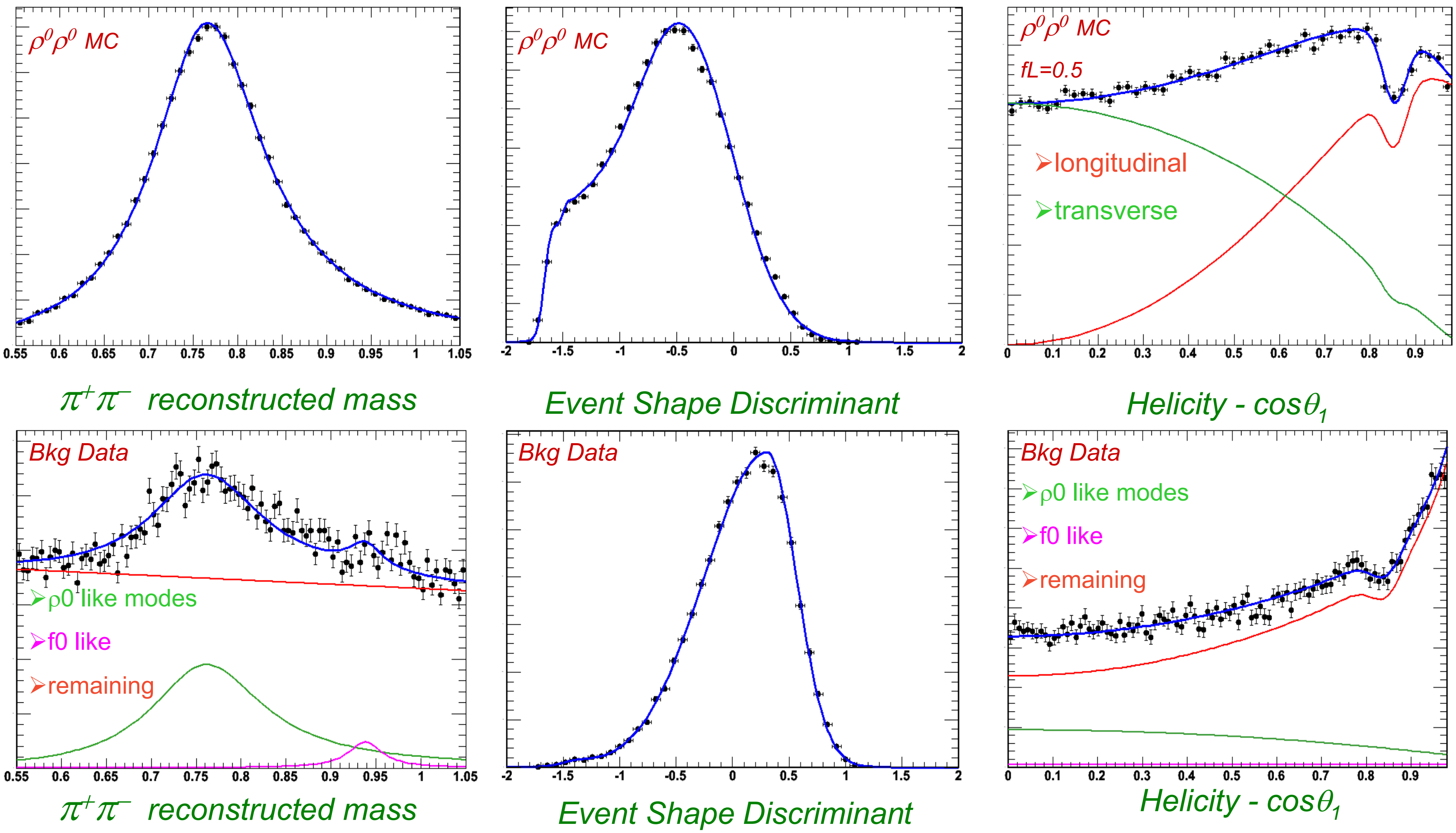
Backgrounds II

❖ Large event count in the Signal Region

More Numerous

- ❖ Self Cross Feed-Like Charmless Cocktail: $B\rightarrow\rho^0\rho^+$, $\rho^+\rho^-$, $\rho^+\pi^-$, $\rho^-\pi^+$, $\rho^0\pi^+$, η'K, $a_1^{\,+}f_0$, $a_1^{\,0}\pi^+$ (~500 evts.).
  - One (or more) mismatched π.
  - Fit simultaneously & study the impact of changing component yields.
  - Several ways to combine Signal-Like & SXF-Like Charmless.
- ❖ Remaining $B\overline{B}$ decays (~2000 evts.).
- ❖ Continuum background (~70000 evts.).
  - Separate Using the NN Discriminant (eShape).
  - Fit to the sideband & allow (some) parameters to float in the Data fit.

❖ Mass, eShape and helicity distributions for $B^0 \to \rho^0 \rho^0$ and Continuum PDFs.

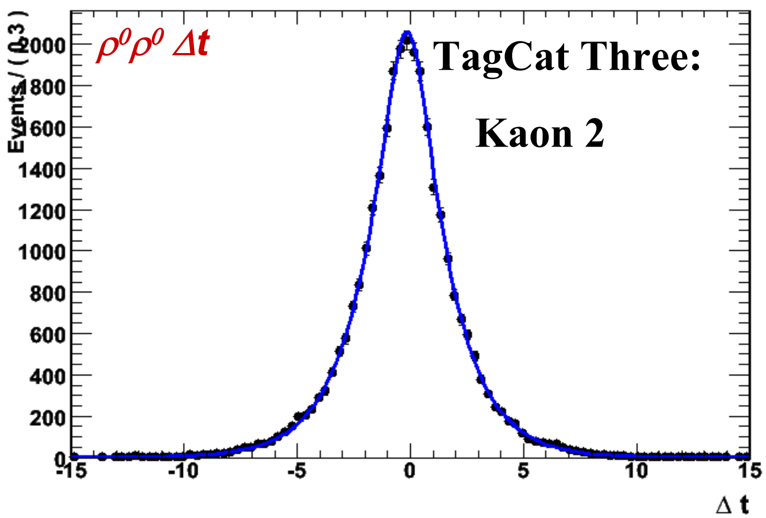


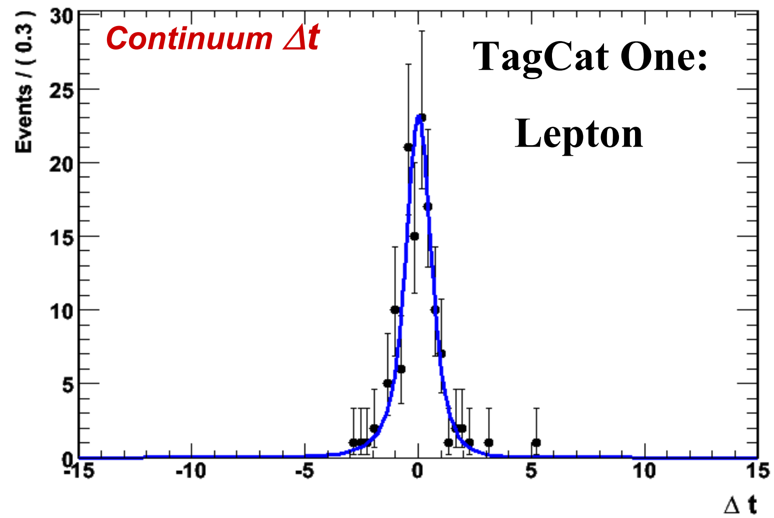
Time Dependence

❖ Δt is fitted with a **CP Model PDF** convoluted with a resolution function.

$$
\begin{aligned}
F_{Q_{tag}}^{\rho^0\rho^0}(\Delta t) \sim \frac{e^{-|\Delta t|/\tau}}{4\tau}\times \quad & \{1 - Q_{tag}\Delta w + Q_{tag}\mu(1-2\omega) \\
& + (Q_{tag}(1-2w) + \mu(1-Q_{tag}\Delta\omega))\,[S\sin(\Delta m_d\Delta t) - C\cos(\Delta m_d\Delta t)]\} \\
\mathcal{R}_{\rm sig}(\Delta t, \sigma_{\Delta t}) \quad = \quad & f_{\rm core} G\left(\Delta t, \mu_{\rm core}\sigma_{\Delta t}, \sigma_{\rm core}\sigma_{\Delta t}\right) \\
& + f_{\rm tail} G\left(\Delta t, \mu_{\rm tail}\sigma_{\Delta t}, \sigma_{\rm tail}\sigma_{\Delta t}\right) + f_{\rm out} G\left(\Delta t, \mu_{\rm out}, \sigma_{\rm tail}\right)
\end{aligned}
$$

➢ $Q_{tag}=\pm 1$ for $B^0,\overline{B}^0$; ω, $\Delta\omega$ are the mistag fraction and error for each Tagging Category; $G(\mu,\mu_0,\sigma)$ is a Gaussian with the bias μ_0 and standard deviation σ.

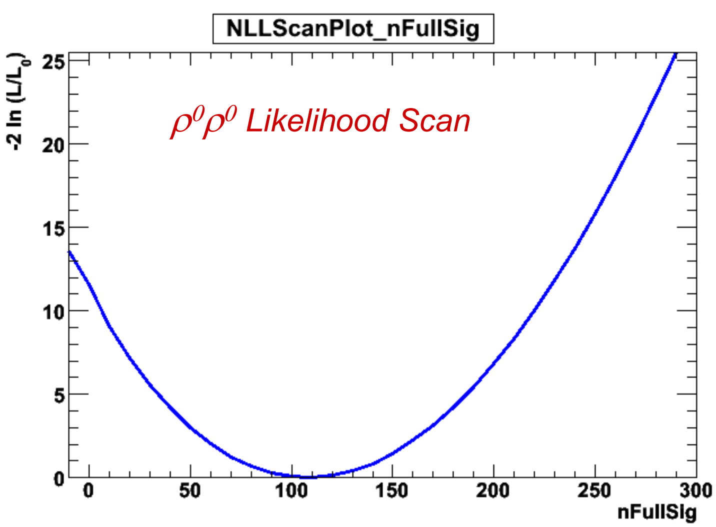




Raw ML Fit

❖The Maximum Likelihood fit is performed in multiple stages:

- CP-Symmetric Fit with Continuum mass-helicity & eShape parameters floated.
- CP-Symmetric Fit with Δt parameters floated.
- Full (CP dependent) fit:



Parameter	Value	+Error	-Error
C	**0.20**	**0.82**	**0.70**
S	**0.26**	**0.67**	**0.73**
polarization f_L	0.71	0.13	0.15
4π Yield	3.7	29.7	25.3
BBbar Yield	2356	151	150
Bkg Yield	68691	284	283
Chls Yield	669	89	87
$a_1\pi$ Yield	248	52	49
$\rho^0\rho^0$ Yield	**107.0**	**35.3**	**34.3**
$\rho^0 f_0$ Yield	10.2	21.7	20.1
$f_0 f_0$ Yield	4.4	7.8	4.9
$\rho^0\pi\pi$ Yield	-23.5	39.3	35.2

Validation I: Toys

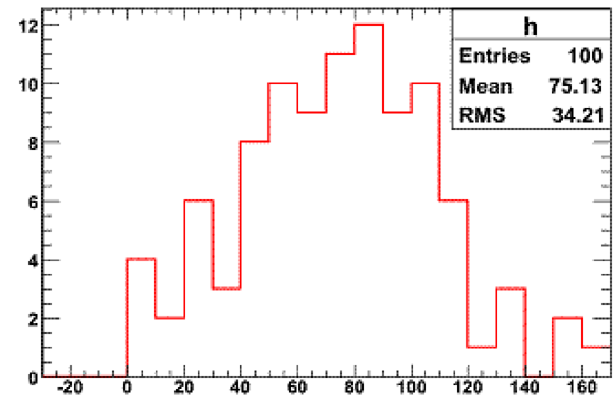
❖ Construct 100 Toy Datasets for Embedded MC (with Chls., $B\bar{B}$ & Continuum generated from PDFs).

➢ Apply to various sets of initial parameters.

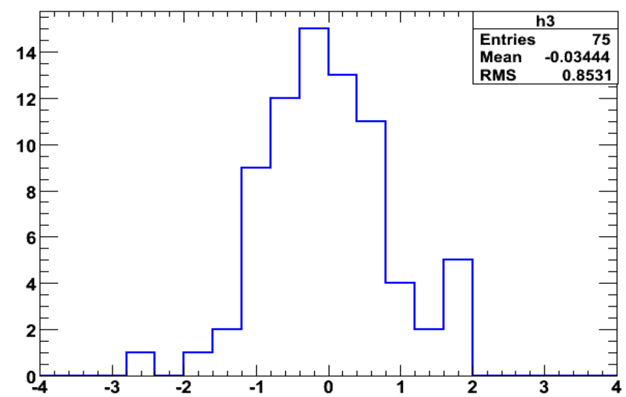
Typical Configuration

Parameter	Given	Fitted	RMS
$\rho^0\rho^0$ Long	56	59.9	30.6
$\rho^0\rho^0$ Tran	29	29.7	19.1
$\rho^0\pi\pi$	0	-10.8	48.4
4π	0	-4.1	36.4
$\rho^0 f_0$	6	12.8	25.4
$f_0 f_0$	6	3.8	8.9
S	-0.4	-0.43	0.98
C	0.0	0.06	0.86
S Pull	0.0	-0.02	0.98
C Pull	0.0	0.14	1.14

Longitudinal Signal

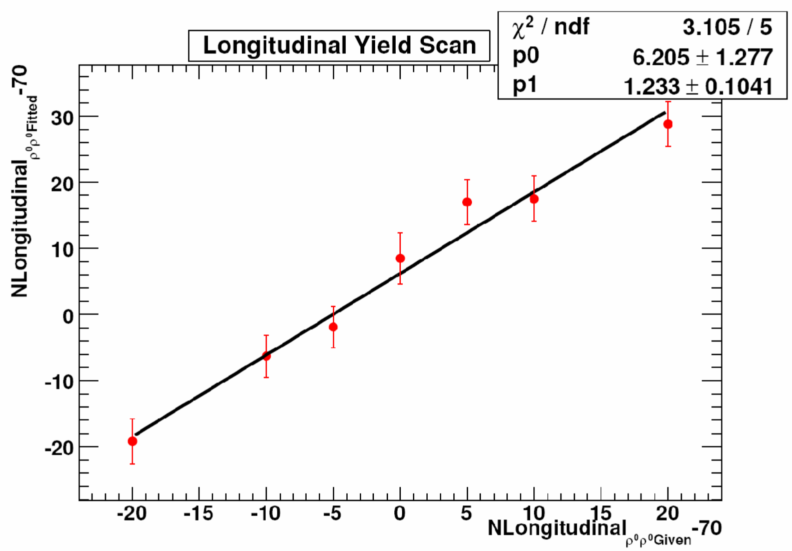


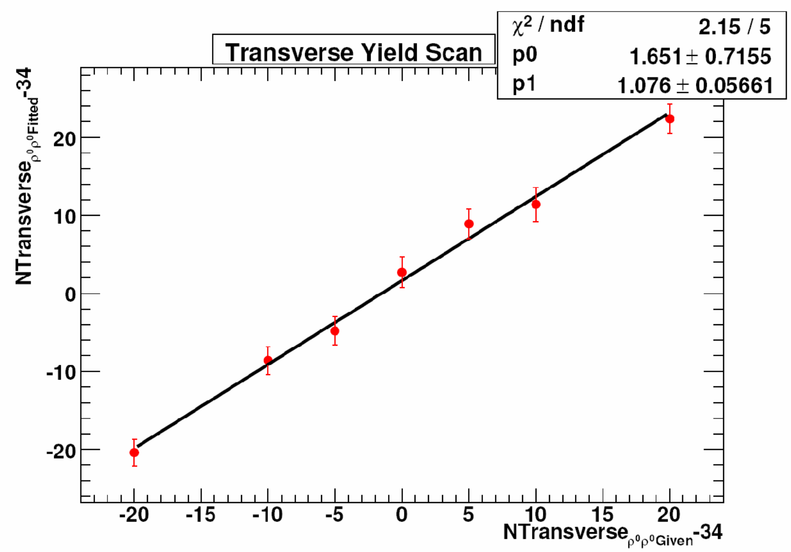
Pull on S



Validation II: Fit Bias

- Vary Longitudinal and Transverse Yields about their expected value.
- The bias is 6.2±1.3 for the Longitudinal and 1.7±0.7 for the Transverse yield.

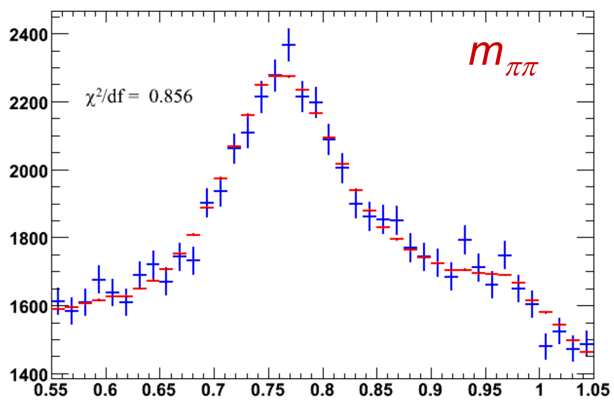


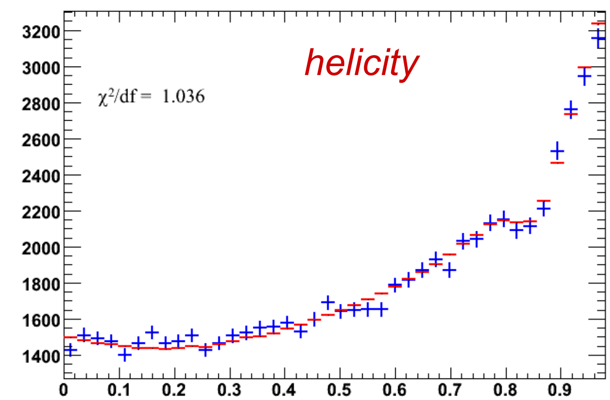


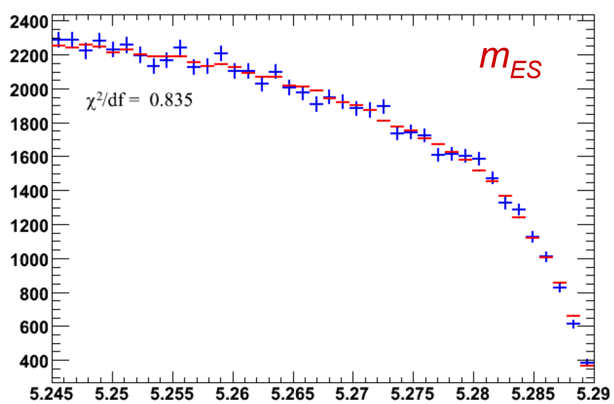
- Similarly, vary S & C.
- The bias is 0.03±0.06 for S and 0.01±0.03 for C.

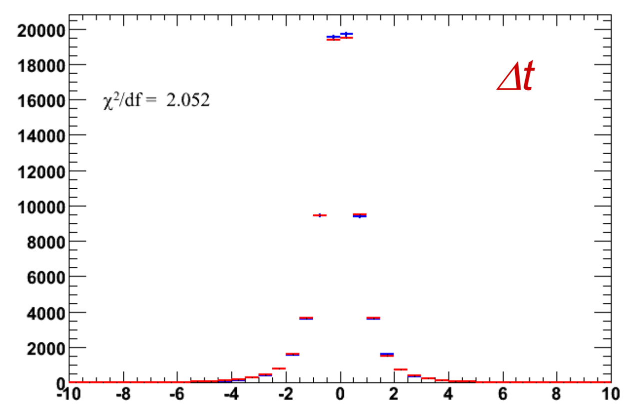
Validation III: Direct Projections

- Generate toy MC (red) using parameters returned by the fit.
- Overlay with the Data (blue).





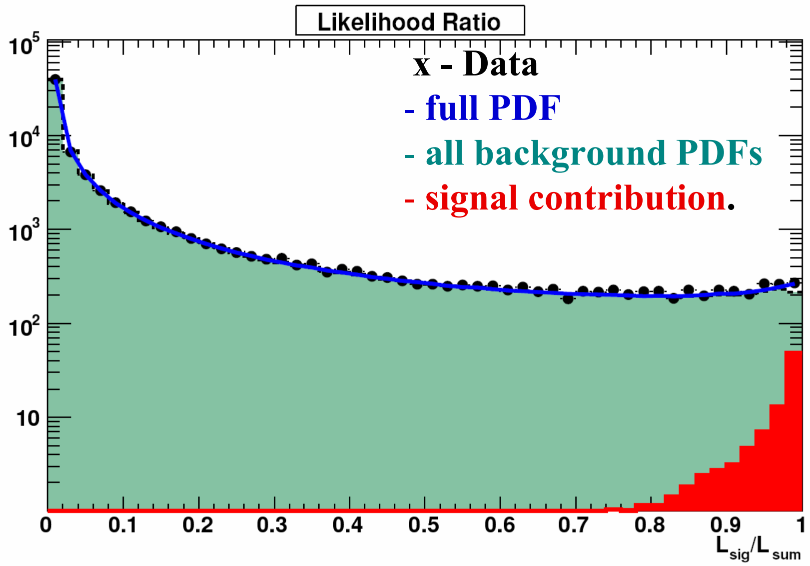




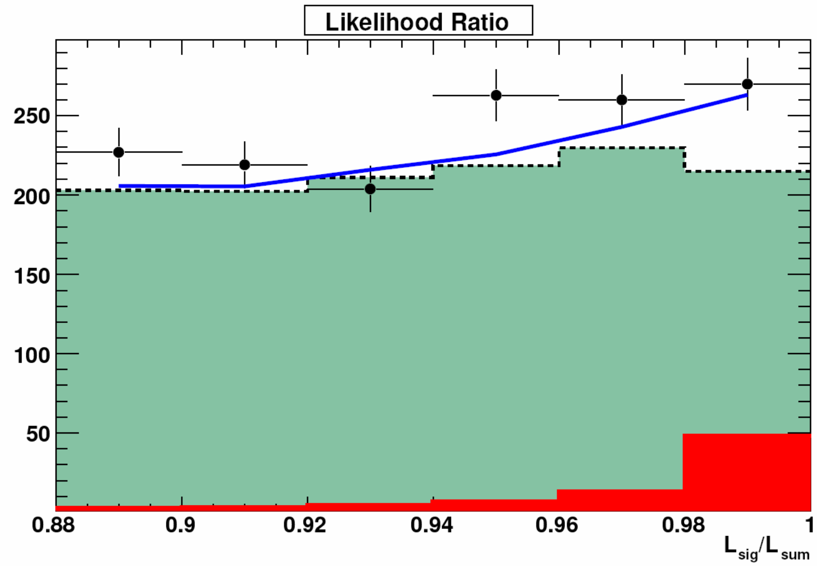
Validation IV: Likelihood Ratios

❖ Likelihood Ratio: $\mathcal{L}_{sig}/\mathcal{L}_{Tot}$.

❖The PDF fit (blue) is a good match to the Data (black) with χ^2/ndf=1.20.



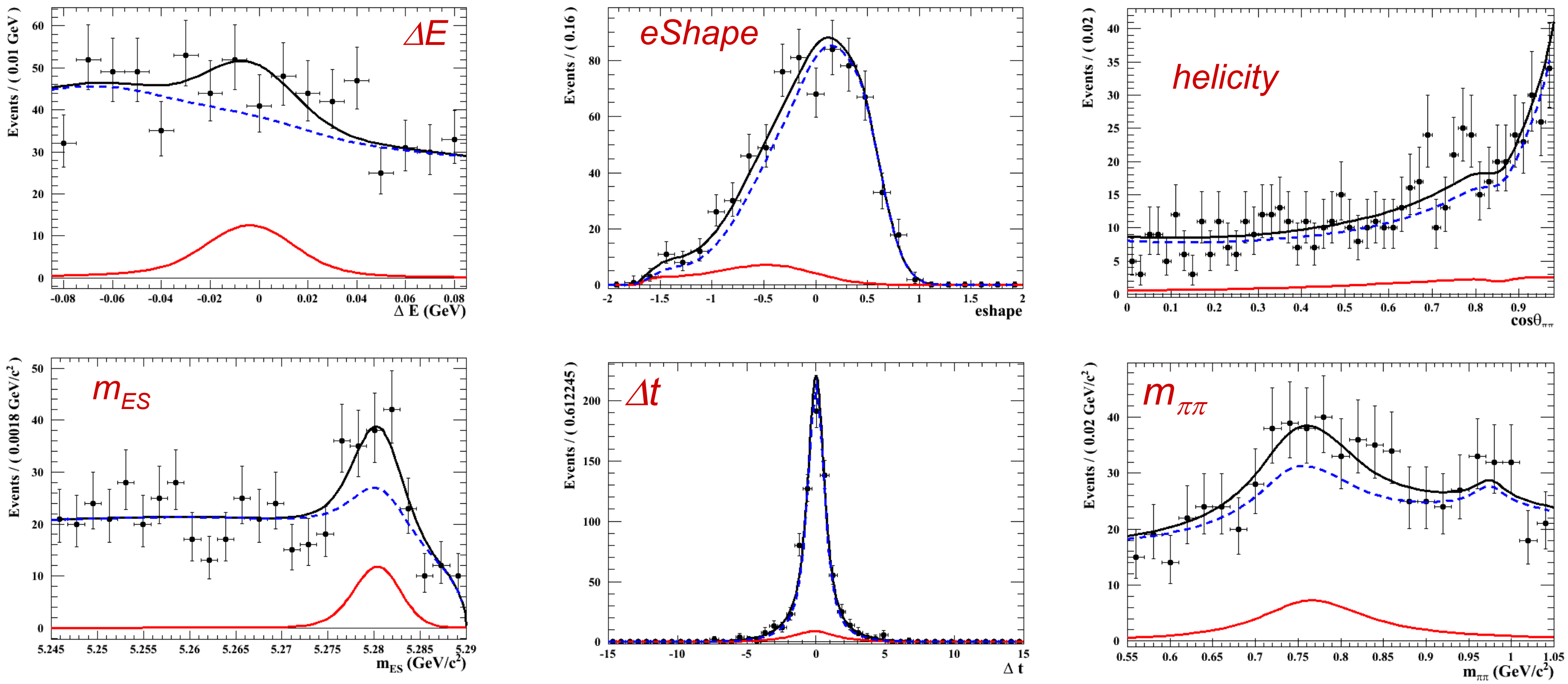
Full Range



Signal Region

Validation V: Projection Plots

❖ **We place a likelihood cut to enhance the signal/background ratio and project the multidimensional fit onto its parameters.**



- Projection plots onto ΔE, eShape, helicity, m_{ES}, Δt and $m_{\pi\pi}$. $B^0 \to \rho^0 \rho^0$ signal is in red, background in blue and the sum in black.

Systematics I:

- ❖ Scale factors (don't affect significance)
  - Tracking efficiency (0.5%/track)
  - PID efficiency (0.5%/track, evaluated with $D\pi$ control sample)
  - Vertex χ^2 cut (<1%)
  - Other selection cuts (<1%)
  - B Counting (1%)
  - Interference with $a_1\pi$ final state (~14evts).
    - ☞ Studied with toyMC
- ❖ Other systematic effects (which affect significance)
  - Fit bias (~2 evts).
    - ☞ Mainly due to correlations
  - PDF Shapes (~5evts).
    - ☞ Studied by varying PDF parameters.

Systematics II:

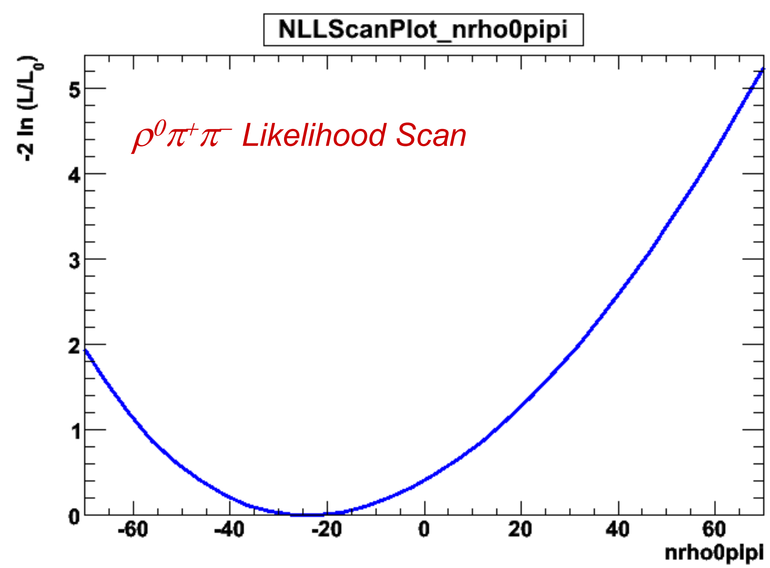
Source	$B^0\to\rho^0\rho^0$	$B^0\to\rho^0 f_0$	$B^0\to f_0 f_0$	$B^0\to\rho^0\pi^+\pi^-$	$B^0\to 4\pi$	f_L
Multiplicative (i.e. →0 as Signal→0)						
Number of B mesons	1.1%	1.1%	1.1%	1.1%	1.1%	-
Track multiplicity cut	1.0%	1.0%	1.0%	1.0%	1.0%	-
Thrust angle cut	1.0%	1.0%	1.0%	1.0%	1.0%	-
Vertex requirement	2.0%	2.0%	2.0%	2.0%	2.0%	-
PID cut	2.0%	2.0%	2.0%	2.0%	2.0%	-
Track finding	2.0%	2.0%	2.0%	2.0%	2.0%	-
MC statistics	<1%	<1.%	<1%	<1%	<1%	<0.01
Interference	**14*evts***	10*evts*	6*evts*	15*evts*	6*evts*	0.051
Additive (i.e. unchanged as Signal→0)						
PDF variation	**4.6*evts***	4*evts*	3*evts*	7*evts*	7*evts*	0.030
Charmless BR	2.2	2.9	0.3	0.2	1.9	0.010
Fit bias	2.0	2.5	0.9	4.8	3.6	0.009
Total	**16*evts***	12*evts*	7*evts*	18*evts*	11*evts*	0.048

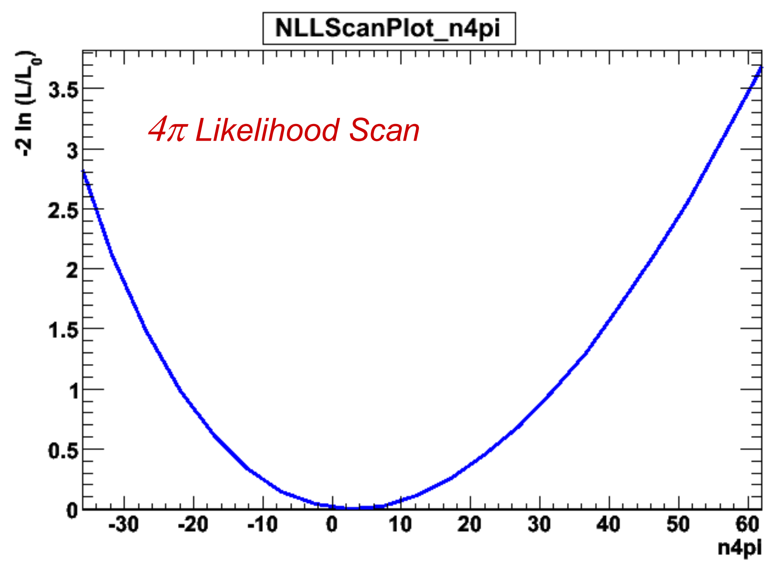
❖ **Interference (primarily with $a_1\pi$) & PDF shape variation are the main sources of error.**

Results I:
Non-Resonant Modes

❖ **We obtain the upper limits of 8.8x10^{-6} for $B^0 \rightarrow \rho^0 \pi^+ \pi^-$ and 23.1x10^{-6} for $B^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ at 90% CL.**

- The mass range is the same as all other modes ($0.55 < m_{\pi\pi} < 1.05$).
- Belle Limits: $BR_{\rho\pi\pi} < 11.9 \times 10^{-6}$, $BR_{4\pi} < 19.0 \times 10^{-6}$ (with $0.55 < m_{\pi\pi} < 1.70$).





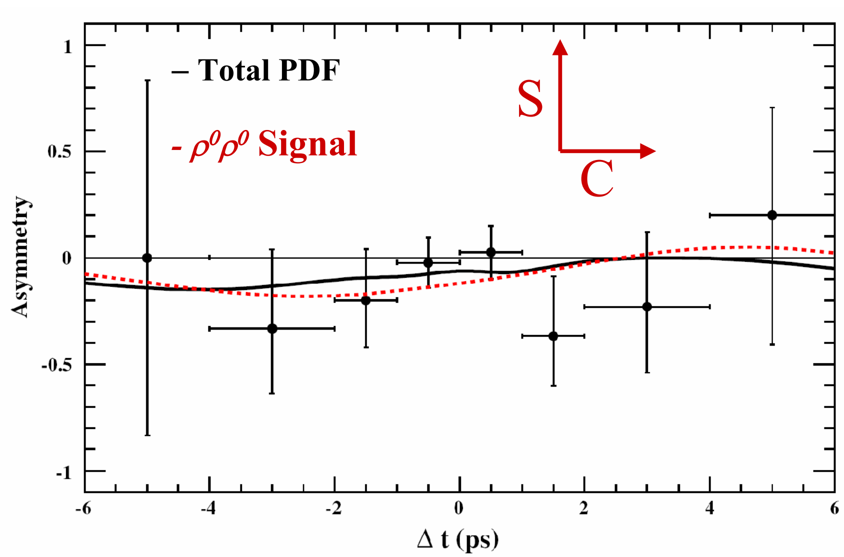
Results II:
Signal Modes

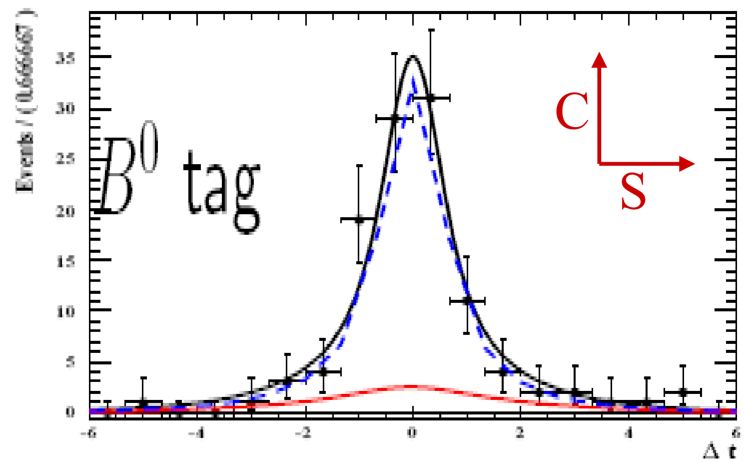
- $N_{\rho^0\rho^0} = 99.1^{+35}_{-34}(stat.) \pm 16(syst.)$
  - The significance (including systematics) is **3.1σ**
  - $f_L = 0.75^{+0.11}_{-0.14}(stat.) \pm 0.05(syst.)$
  - $N_{\rho^0 f_0} = 3^{+22}_{-20}(stat.) \pm 12(syst.)$, $N_{f_0 f_0} = 7^{+8}_{-5}(stat.) \pm 7(syst.)$.
  - $N_{\rho^0\pi^+\pi^-} = -13^{+39}_{-35}(stat.) \pm 18(syst.)$, $N_{4\pi} = 8^{+30}_{-25}(stat.) \pm 11(syst.)$.
- $BR_{\rho^0\rho^0} = [0.92^{+0.33}_{-0.32}(stat.) \pm 0.14(syst.)] \times 10^{-6}$
  - $BR_{\rho^0 f_0} < 0.40 \times 10^{-6}$, $BR_{f_0 f_0} < 0.19 \times 10^{-6}$ at 90% CL.

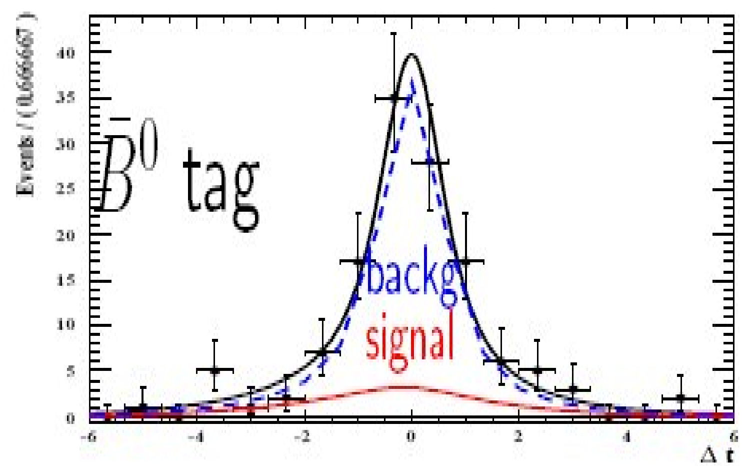
Results III:
CP Parameters

- ❖ $S_L^{00} = 0.3 \pm 0.7(\text{stat.}) \pm 0.2(\text{syst.})$
- ❖ $C_L^{00} = 0.2 \pm 0.8(\text{stat.}) \pm 0.3(\text{syst.})$
- ➢ Correlation = 0.035.

$$\mathcal{A}_{CP}(\Delta t) = -C_L^{00}\cos\Delta m\Delta t + S_L^{00}\sin\Delta m\Delta t$$



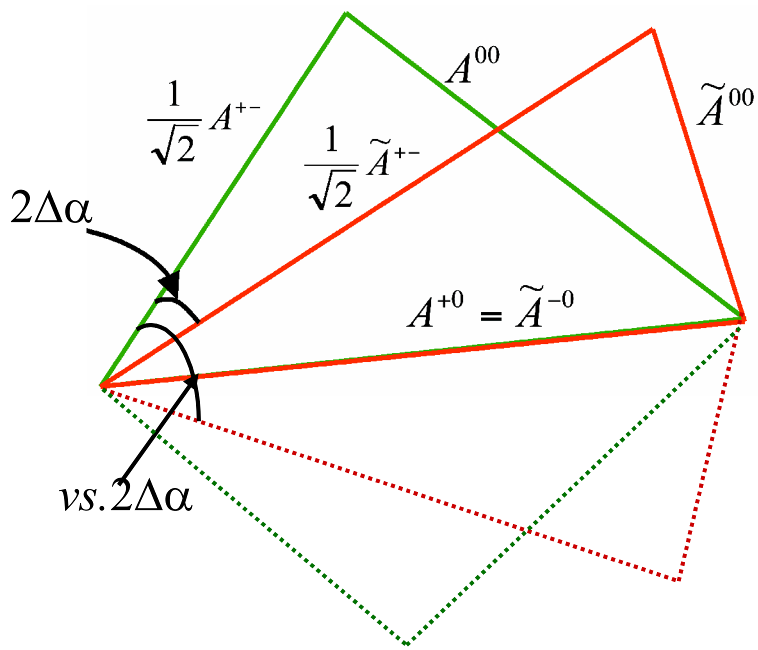


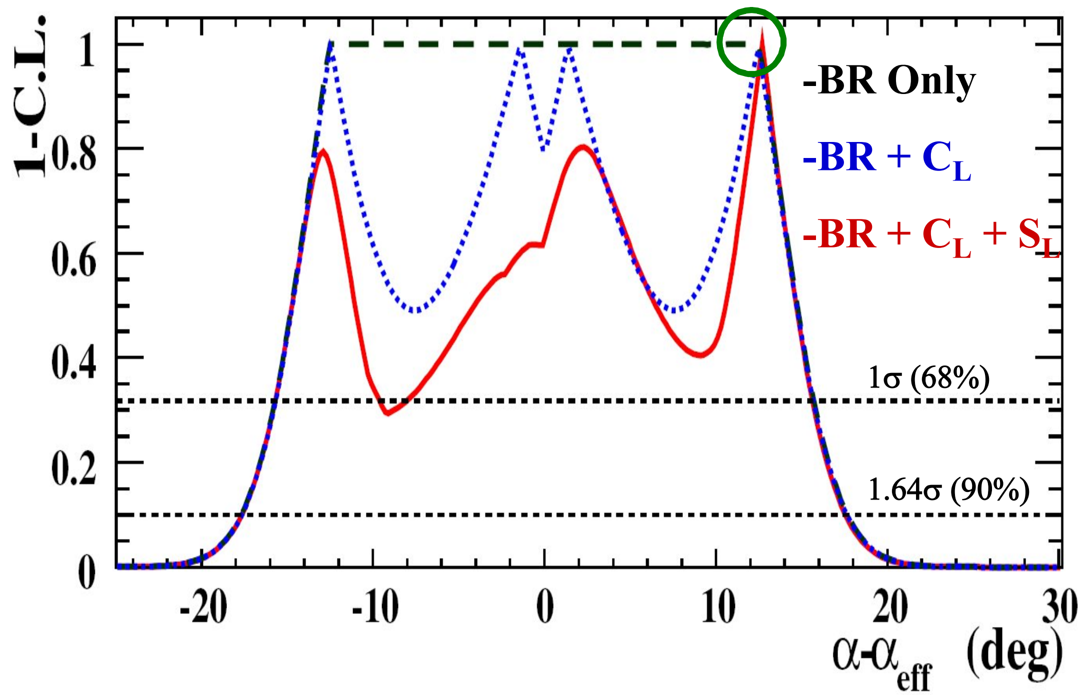


$\chi 2(\alpha)$ Scan

❖ Perform the Isospin Analysis & Scan over α.

❖ Ambiguities:



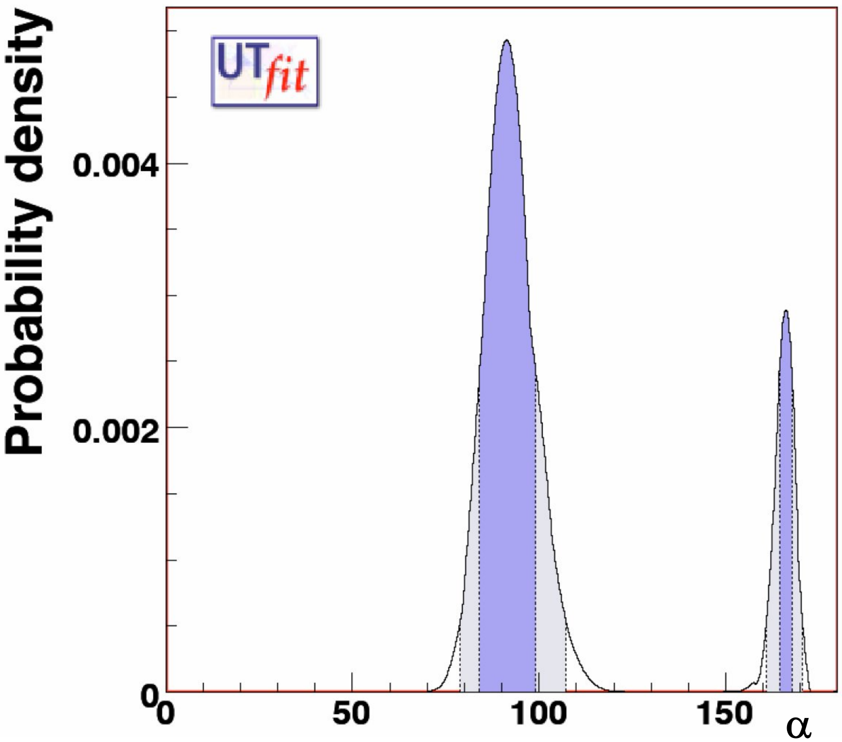


❖ **$|\Delta\alpha|<15.7^o$ (17.6^o) at 1σ (90%) CL, $\alpha=(82.6^{+32.6}_{-6.3})^o$ at 1σ.**

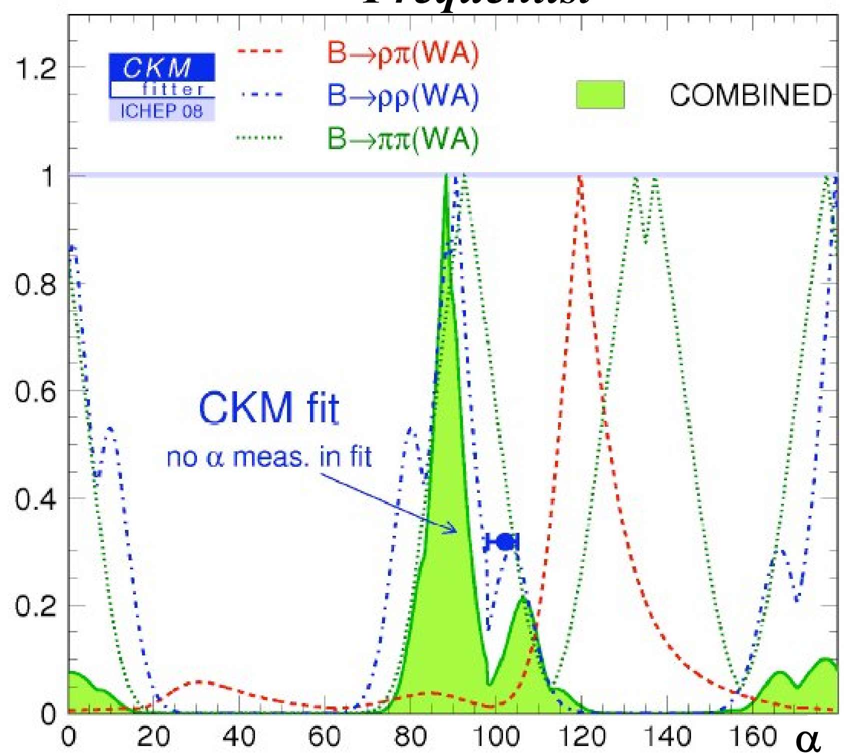
Implications for α: CKM & UT Fits

❖ Combine the $B \to \rho\rho$ results with other measurements (primarily $B \to \rho\pi$, $B \to \pi\pi$).

Bayesian



Frequentist



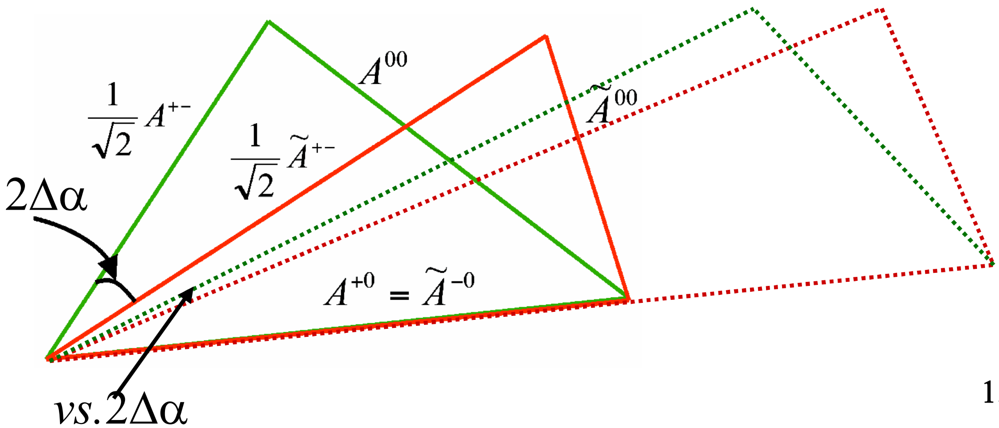
➢ **UT Fit: $\alpha=(91\pm8)^o$ @ 1σ.**

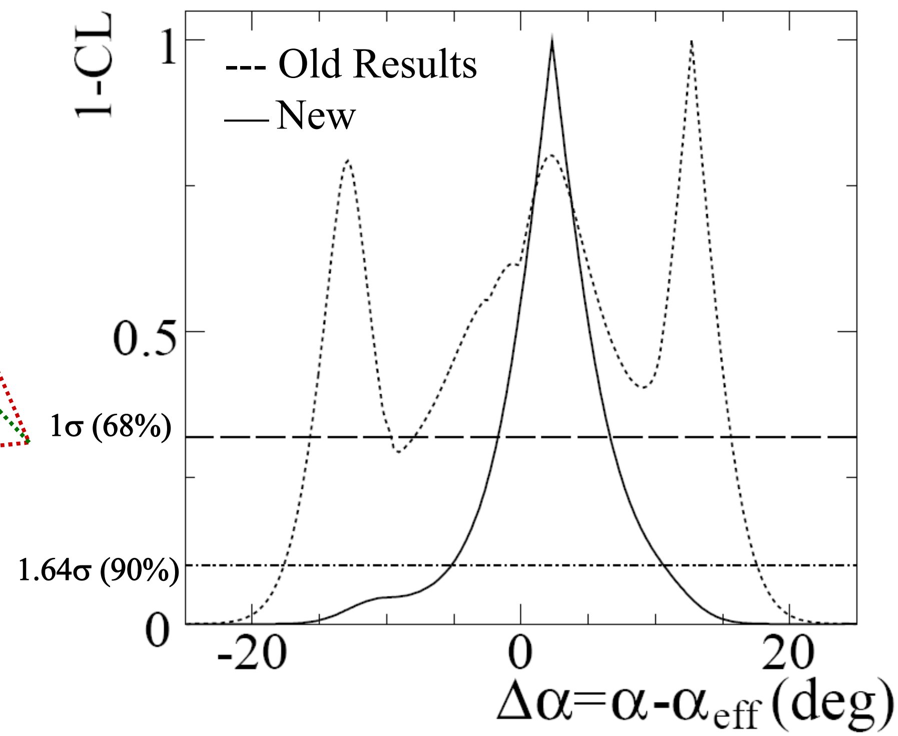
➢ **CKM Fit: $\alpha=(81.1^{+17.5}_{-4.9})^o$ @ 1σ.**

Updated Results

- arXiv:0901.3522: BR($\rho^+\rho^0$)=[23.7±2.0]x10^{-6} (piror: [16.8±3.2]x10^{-6})

- Reduces the size of $\Delta\alpha$.

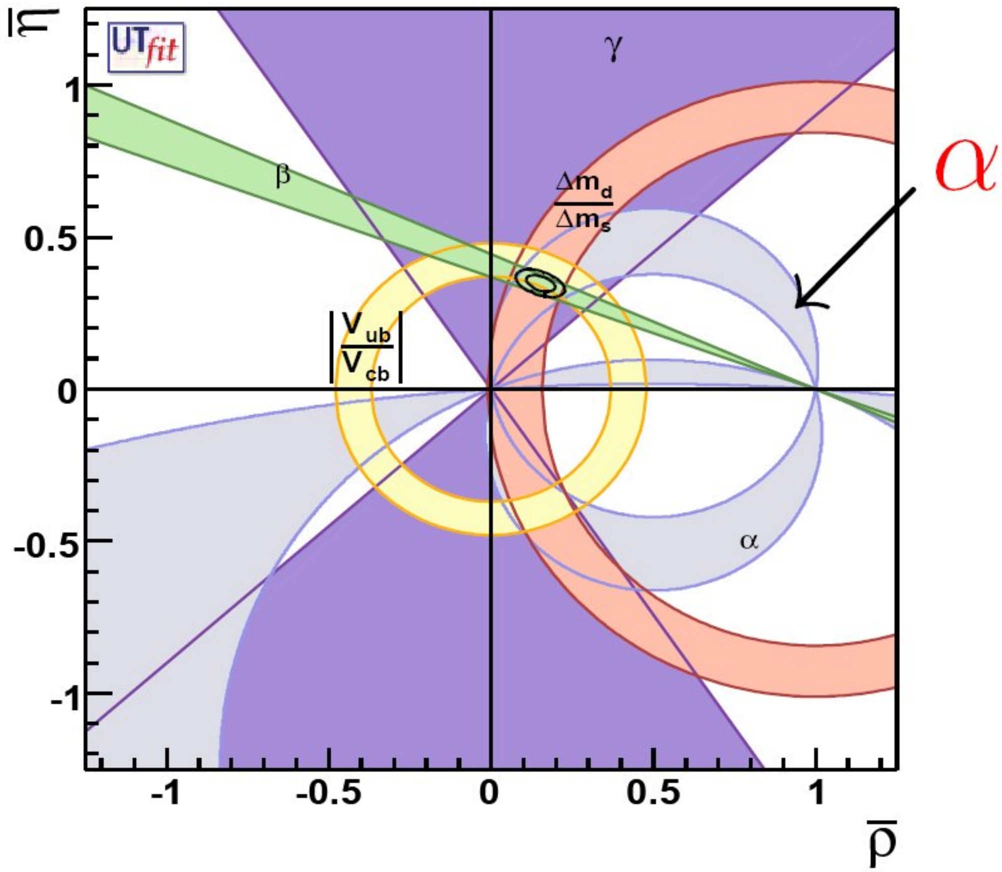




- **$-1.8^o<\Delta\alpha<6.7^o$, $\alpha=(92.4^{+6.0}_{-6.5})^o$ at 1σ.**

Implications for the CKM Matrix

❖ **Further restrict the CKM parameters ρ & η.**



Implications for the LHC

- B-factory searches restrict new physics effects to be <10%.
- Masses ~300GeV-1TeV for the same couplings.
- Most likely to restrict the couplings when the mass-peaks are seen.

Conclusions

- **Evidence for $B^0 \to \rho^0\rho^0$ signal:**
  - **BR=$(0.92 \pm 0.33 \pm 0.14)\times10^{-6}$ at 3.1σ significance.**
  - **f_L=$0.75 \pm 0.14 \pm 0.05$.**
- **No significant evidence for $B^0 \to f_0\rho^0$, $B^0 \to f_0 f_0$, $B^0 \to \rho^0\pi^+\pi^-$, $B^0 \to \pi^+\pi^-\pi^+\pi^-$ decays.**
- **CP Parameters:**
  - **S_L=$0.3 \pm 0.7 \pm 0.2$**
  - **C_L=$0.2 \pm 0.8 \pm 0.2$**
- **Performed Full Isospin Analysis & obtained limits for Penguin Contributions to α:**
  - **$|\Delta\alpha|<15.7^o$ at the 1σ level.**

Backup